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NATURAL GAS VARIABILITY IN CALIFORNIA: ENVIRONMENTAL IMPACTS AND DEVICE PERFORMANCE

LITERATURE REVIEW AND EVALUATION FOR RESIDENTIAL APPLIANCES

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit electricity and natural gas customers.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
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- Renewable Energy Technologies
- Transportation

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For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier/ or contact the Energy Commission at 916-654-5164.

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Abstract

California is preparing to incorporate liquefied natural gas (LNG) into its supply system. The physical properties and chemical composition of LNG differ on average from current natural gas (NG) supplies. This report reviews existing information on the interchangeability of LNG with conventional NG for use in residential appliances. The study of interchangeability started with the widespread introduction of natural gas. Early work yielded indices for predicting flame lift, flashback, yellow tipping, and incomplete combustion based on fuel properties. Most important is the Wobbe number, which is proportional to the rate of energy delivery in conventional residential appliance burners. These indices along with new experiments have been used to study interchangeability for the past six decades. In recent decades, air pollutant emissions have joined safety and performance as key metrics of interchangeability. Several major studies of LNG interchangeability on contemporary equipment have been completed recently. Existing information suggests that appliances tuned with NG having the average properties of current California NG should not experience operational problems with LNG blends expected in the state. LNGs with higher Wobbe numbers lead to carbon monoxide emissions in some burners and sharp increases in nitrogen oxides emissions in full premix burners without feedback control. The effect of gas quality variability on emissions of ultrafine particles and formaldehyde has not yet been studied.

Keywords: Appliances, carbon monoxide, end-use equipment, experimental studies, indoor air quality, interchangeability, liquefied natural gas, nitrogen oxides, pollutant emissions

Executive Summary

Introduction

In response to increasing demand for natural gas across the western United States, California will need to integrate new supplies, including liquefied natural gas (LNG) from the Pacific Rim. The physical properties and chemical composition (that is, the gas quality) of these LNG mixtures differ on average from the natural gas (NG) currently distributed in the state. The California Energy Commission (Energy Commission) has asked the Gas Technology Institute (GTI) and Lawrence Berkeley National Laboratory (LBNL) to evaluate potential effects associated with use of future LNG supplies on existing equipment in California. In the industry's terminology, the study is examining the "interchangeability" of potential LNG supplies in the existing infrastructure. As part of this study, LBNL is examining the effect of gas quality on performance and air pollutant emissions of residential appliances.

Residential appliances are a focus of the overall study for several reasons. The residential market comprises the vast majority of individual devices and natural gas customers. Appliances vary in age, state of repair, design, and technology. The population includes many devices that have not been serviced in years and that may not be installed, adjusted, or operated as intended. As a group, appliances cannot readily be readjusted, or even inspected to determine if gas quality changes have resulted in adverse impacts. It is thus imperative to examine potential impacts in advance.

The gasification process through which LNG is produced removes inert components (such as carbon dioxide and nitrogen), impurities (such as sulfur), and hydrocarbons containing five or more carbon atoms per molecule (C5+). The resulting mixtures typically contain non-methane hydrocarbons (NMHC) with two to four carbon atoms (C2-C4) in larger percentages than are present in current California supplies. These composition differences lead to LNG blends that contain more energy per volume—that is, have a higher energy density, than current supplies. The LNG blends also have the property that they deliver more energy per time (heat input rate) relative to current natural gas when used in conventional "partial premix" appliance burners. Partial premix burners provide only a portion of the air needed to fully combust the gas in the jet of air and gas that exits the burner ports; the remaining air is provided from the surroundings or via secondary air inlet ports. This heat input rate is measured by the Wobbe number (WN), an important metric of gas interchangeability. Wobbe numbers of Pacific Rim LNGs fall mostly in the range of 1390 to 1440 British thermal units per standard cubic foot (Btu/scf), whereas current volume-weighted averages in Northern and Southern California are in the range of 1330 to 1340 Btu/scf. A change from current NG to an unaltered LNG blend thus could raise the heat input rate by about 8%. The Public Utilities Commission has approved a Wobbe number limit of 1385 Btu/scf for Southern California; thus the average change of heat input expected with LNG is only about 4% or less. However some areas could experience a larger change.

Task Objectives

The overall objective of this report is to review existing studies of substantial relevance to the evaluation of gas interchangeability for residential appliances. The review compiles information from varied sources consisting of both publicly available and limited distribution reports, conference presentations, and other presentations. The reviewed research was conducted by staff of gas industry corporations (primarily utilities and line distribution companies), by consultants hired by industry interests (including LNG suppliers), by government researchers, and, in one recently completed study, by consultants to a government agency in the United Kingdom. This report attempts to review and synthesize this information comprehensively.

This report summarizes what is and is not known about the potential impacts of gas quality changes on appliance operability, safety, performance, and pollutant emissions. An important facet of this effort is an evaluation of information gaps—that is, questions and potential concerns that have not been adequately addressed in past studies. This report informed the design of a new experimental study that will expand the knowledge base on potential impacts of gas quality variability on appliance emissions and performance. The study plan has been submitted as the Final Task 8 report, and the work is being conducted as Task 9 of this project.

Summary Findings

The response of conventional natural gas appliances and appliance technologies to changes in fuel composition and Wobbe number has been studied extensively. Much of the existing work has focused on basic operability and safety, specifically including ignition, flame stability, flame quality, and excessive carbon monoxide emission. Flame stability issues include lifting of the flame from the burner head, or, at the other extreme, advancement of the flame back into the burner head (flashback). Poor flame quality can be expressed as a tendency towards lifting or flashback, or the appearance of yellow tips that indicate soot formation. Soot is important both as a pollutant emitted into the air and for its potential deleterious effects on device operation when deposits build up on sensitive components. Carbon monoxide (CO) is a fundamental safety concern since excessive emissions from a non-venting or an improperly vented appliance can lead to high concentrations and potential CO poisoning of occupants in a residence. In recent years, concerns have expanded to include emissions of nitrogen oxides (NO_X), potential changes to surface and component temperatures, and potential effects on safety feature performance.

The following factors may affect whether a given device will experience any adverse performance or emission impacts as a result of supply gas quality changes:

• Device technology and design characteristics. This includes burner type, combustion chamber design, primary aeration, amount of excess air, and any other physical features that may affect combustion or be affected by changes in flame temperature, flame length, or other flame properties.

- Device operational condition. This category includes factors related to device set-up, maintenance, device and component quality, and other factors related to device installation, as listed below:
 - o Properties of the natural gas used for last rating and adjustment.
 - Quality of device installation, rating, and adjustment.
 - o Possible tampering or adjustment made following last rating/adjustment.
 - Age/wear of device and state of repair of device components.
 - o Other factors including gas supply pressure and stability.
- Properties and composition of substitute gas.
- *Device use patterns*. Device operational patterns may vary among users, including more or less steady-state or intermittent operation, routine or extreme application, and other factors.
- *Environmental conditions*. Important parameters include air temperature, humidity, and pressure (which is primarily dependent on elevation).

The following points summarize what is currently known about the most important potential effects of fuel variability on natural gas appliance performance and emissions. These finding apply when changing the fuel without readjustment of the appliance.

- Natural gases having relatively similar properties (Wobbe numbers within 10% of one another) can be interchanged without concern for affecting operability or flame stability in the vast majority of appliances. Fuel changes may be problematic in specific applications that involve timed processes or that are sensitive to flame temperature or length.
- Increasing fuel Wobbe number can cause flame lengthening. Longer flames may be more likely to impinge on surfaces, potentially causing higher CO emissions and accelerated equipment wear.
- Changes to fuel Wobbe number have a very small effect on energy efficiency for most appliances, and the direction of the effect varies by appliance—that is, with increasing fuel Wobbe number, some appliances experience increased efficiency while others are slightly less energy efficient.
- Increasing fuel Wobbe number leads to higher CO emissions in some appliances. The magnitude of this effect is largest and of most concern in appliances that already have high CO emissions because of an improper air-fuel adjustment, equipment misalignment, or other factor. CO emissions can increase exponentially in relation to the fuel Wobbe number.
- Increasing fuel Wobbe number leads to steadily increasing NO_X emissions in conventional partial premix burners. NO_X emissions increase sharply with fuel Wobbe number in the full premix burners that are commonly used for NO_X

control. In these burners all of the air required for combustion is combined with the fuel prior to the mixture exiting the burner port.

- Increasing fuel Wobbe number can lead to increased soot production and deposition in devices that operate, by design or improper adjustment, with an excessively fuel rich primary combustion zone. This applies mainly to gas fires in which the flame is designed to produce soot for decorative purposes and the soot is then supposed to burn out in an oxygen-rich post flame zone.
- Ultrafine particles and formaldehyde are pollutants of health concern that can be emitted by gas appliances. The effect of changing fuel composition and Wobbe number on emissions of these pollutants has not yet been studied.

Some of the observed effects can be explained by considering basic appliance and burner designs and combustion fundamentals. The trends in both CO and NO_X emissions as a function of fuel Wobbe number are consistent with the expected behavior of partial and full premix combustion burners. Other burner design elements, such as the availability of extra air to complete combustion, can also affect emissions. The potential effects of gas quality changes have not been evaluated for many of the new gas appliance technologies that are expected to enter the market in coming years.

There are several characteristics of in-use equipment that may affect interchangeability. The most important of these are factors related to equipment aging and service, including improper adjustments, component misalignment, material wear, and others.

In practice, the operating patterns for some appliances may be dominated by intermittent operation. Yet most gas interchangeability research to date has examined performance and especially pollutant emissions only during steady burner operation. There is some evidence showing that some pollutant emissions can spike during the burner warm-up phase; the effect of fuel changes on intermittent operation has not been studied adequately.

Several gas interchangeability studies conducted in recent years have examined the effect of adding either N_2 , CO_2 , or air as an inert diluent to reduce the heat value and Wobbe number of actual or simulated LNG blends. The general finding is that dilution of higher Wobbe number LNGs is an effective method to achieve interchangeability in existing residential appliances.

Benefits to California

This research is helping to lay the groundwork for maintaining a safe and reliable natural gas supply in California. The proactive investigation of potential impacts of new supplies, including LNG, will allow the state to set gas quality limits that ensure acceptable operation and pollutant emission levels for the existing population of appliances in the state.

1.0 Introduction

In response to increasing demand for natural gas across the western United States, California will need to integrate new supplies, including liquefied natural gas (LNG) from the Pacific Rim. The physical properties and chemical composition (that is, the gas quality) of these LNG mixtures differ on average from the natural gas (NG) currently being distributed throughout the state. The California Energy Commission (Energy Commission) has asked the Gas Technology Institute (GTI) and Lawrence Berkeley National Laboratory (LBNL) to evaluate potential effects associated with use of future LNG supplies on existing equipment in California. As part of this study, LBNL is examining the effect of gas quality on performance and air pollutant emissions of residential appliances. In the industry's terminology, the study is examining the "interchangeability" of future LNG supplies with natural gases that are currently distributed in the state.

Appliances are an important end-use consideration for a number of reasons. The residential market comprises the vast majority of individual devices and customers of natural gas in the state. Residential appliances vary in age, state of repair, design, and technology. The population includes many devices that have not been serviced in many years and may not be installed, adjusted, or operated as intended. As a group, these devices cannot readily be readjusted, or even inspected to determine after the fact if gas quality changes have resulted in widespread adverse impacts. It is thus imperative to examine the potential impacts of fuel supply changes in advance.

The gasification process through which LNG is produced removes inert components (such as carbon dioxide and nitrogen), impurities (such as sulfur), and hydrocarbons containing five or more carbon atoms per molecule (C5+). The resulting mixtures typically contain non-methane hydrocarbons (NMHC) with two to four carbon atoms (C2-C4) in larger percentages than are present in current and historical California supplies. As a result, the gross calorific value (GCV, also referred to as higher heating value, or HHV) of LNG mixtures is higher than most of the currently distributed gas. Pacific Rim LNG mixtures, which are the most likely to be imported to California, have GCVs in the range of 1075 to 1160 Btu per standard cubic foot (Btu/scf). The systemwide averages for Pacific Gas & Electric (PG&E) and Southern California Gas (SCG) service areas (Northern and Southern California, respectively) are approximately 1010 to 1020 Btu/scf.1 Wobbe numbers (WN)2 of the Pacific Rim LNGs fall mostly in the range of 1390 to 1440 Btu/scf, whereas current volume-weighted averages in Northern and Southern California are in the range of 1330 to 1340 Btu/scf. Regarding these numbers, it is important to note that gas quality currently varies both geographically and temporally throughout the state. Importation of LNG will nevertheless result in a significant shift in gas quality for many Californians.

¹ LNG data provided by Edgar Kuipers of Shell trading company; system-average data for California provided/confirmed by Kim Kemp of PG&E and Kevin Shea of SoCal Gas.

² The Wobbe number is equal to GCV divided by the square root of the specific gravity of the gas. It is proportional to the heat input rate for a burner in which fuel gas is supplied at constant upstream pressure through a fixed orifice. Since this design is used in almost all residential appliances, variations in Wobbe number translate directly to variations in heat input supplied to such devices.

In considering the question of how gas quality changes may impact appliance performance and air pollutant emissions, it is important to recognize that natural gas distributed in California must conform to gas quality limits that are codified in tariffs approved by the California Public Utilities Commission (CPUC). Different tariffs cover the distribution systems of PG&E and SCG. Any new supplies must conform to the codified gas quality limits or be processed to meet the limits upon distribution. The CPUC recently approved a Wobbe number limit of 1385 Btu/scf for the SCG distribution system.³ This approval sets a gas quality variation limit for the near term. The residential appliance study being conducted by LBNL is intended to inform not only the near term question of how devices will function within the current gas quality limits, but also to examine the impact of wider gas quality changes.

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³ Decision 06-09-039 (D0609039), September 21, 2006, Order Instituting Rulemaking to Establish Policies and Rules to Ensure Reliable, Long-Term Supplies of Natural Gas to California. Proceeding R0401025.

2.0 Overview and Objectives

The overall objective of this report is to review existing studies of substantial relevance to the evaluation of gas interchangeability (IX) for residential appliances. The intent is to synthesize the available information to determine what is and is not known about the potential impacts of gas quality changes on appliance safety, performance, and pollutant emissions. An important component of this work is an evaluation of information gaps—that is, questions and potential concerns that have not been adequately addressed in past studies.

This review focuses on information that has not previously been reviewed and synthesized comprehensively. Major areas of relevant background material that have been addressed adequately in other publicly available documents are covered here in a limited way. There are two excellent overviews of the natural gas interchangeability issue, both of which are available free to the public on the American Gas Association (AGA) website.⁴ The document White Paper on Natural Gas Interchangeability and Non-Combustion End Use was produced by a group of knowledgeable representatives of gas industry stakeholders who convened under the moniker of the Natural Gas Council (NGC+) Interchangeability Working Group (NGC+ 2005). The NGC+ report includes a series of appendices that provide more detailed information on specific areas of interest. Appendix D of the NGC+ document (Kuipers 2005) examines the impact of gas quality change in the context of combustion fundamentals and specifically focuses on burners common to residential appliances. The second overview is a technical background document prepared for the AGA Building Energy Codes and Standards Committee (Williams 2006). The two main approaches to predicting interchangeability in the United States—the AGA and Weaver multiple index methods—are covered in Appendix D of the NGC+ document and more comprehensively in a recent AGA conference paper (Halchuk-Harrington and Wilson 2006).

This report begins with a brief summary of interchangeability concerns and metrics. This list was developed from the sources that are reviewed in this report. It is presented prior to discussion of the source material because it provides a context for this review in addition to summary descriptions of many terms that are used in the actual study reviews.

Next follows a synopsis of existing IX studies. This synopsis includes the most relevant conclusions from these studies, broadly grouped by the technical objective of the work, and serves as a context for the summaries of the individual studies that follow. The predominant focus is on experimental studies that directly examine gas interchangeability. The body of work covered here spans seven decades and includes a widely heterogeneous collection of source material. These investigations have been conducted for many purposes including determination of local gas quality limits, systematic studies of IX effects, and development/revision of IX indices. A variety of organizations have performed IX studies, including utilities, public and private laboratories, and consultants to gas industry entities. The amount and availability of documentation varies widely, and the vast majority of these studies have not been subject to formal scientific peer review. Lastly, the overview briefly reviews studies that provide relevant information about pollutant emissions from natural gas appliances, specifically focusing on those that have not yet been examined in the context of interchangeability. Summaries of

⁴ www.aga.org/Content/NavigationMenu/Operations_and_Engineering/Gas_Quality1/Gas_Quality.htm

individual studies, with more explanatory detail follow this overview. These individual summaries are grouped by technical objective in the same manner presented in the synopsis.

The report concludes with a synthesis of the available information, organized around specific IX concerns.

To aid readers who are unfamiliar with gas appliance designs and technologies, relevant background information is compiled into Appendix A. Appendix A describes equipment and technologies common to residential appliances and some commercial devices that are similar in design or application to residential units.

3.0 Interchangeability Concerns

Chief among natural gas IX concerns are the potential adverse impacts associated with end use. This review focuses on information and evaluations of IX impacts associated with residential appliances; it includes some related work examining small commercial devices that use the same technologies, are designed for similar applications (such as cooking) or have similar characteristics of being used widely in close proximity to people. Concerns include safety, equipment performance, and air pollutant emissions.

Basic operability and safety are the foundation concerns for gas interchangeability. Included in these concerns are ignition, flame stability, flame quality, and excessive carbon monoxide emission. Flame stability issues include lifting of the flame from the burner head, or at the other extreme, advancement of the flame back into the burner head (flashback). Poor flame quality can be expressed as a tendency towards lifting or flashback, or the appearance of yellow tips that indicate soot formation. Carbon monoxide (CO) is a fundamental safety concern since excessive emissions from a non-venting or an improperly vented appliance can lead to high concentrations and potential CO poisoning of occupants in a residence. These basic performance and safety issues are of real concern when switching among fuel gases having very different compositions and properties (such as producer gas versus natural gas), but they are of much less or in some cases no concern (for example, for flashback) when switching among natural gas mixtures.

The most important environmental impact associated with residential and small commercial gas appliances is emission of air pollutants. Overall, NG is considered a relatively clean fuel and its use in many sectors (such as electricity generation and internal combustion) can lead to much lower emissions than competing fuels. The focus here is on changes in emissions that may result from changes to the NG supply.

Human exposure associated with gas appliance emissions can occur indoors at the location of emissions (such as in a residence or commercial establishment), indoors or outdoors near one or more sources (such as in an adjoining residence or in the same neighborhood), or throughout an urban or regional air shed.

Pollutants associated with gas appliance use include both primary and secondary pollutants. Primary pollutants are compounds emitted directly from the source, such as CO and nitrogen oxides (NO_X , which principally includes nitrogen oxide, NO, and nitrogen dioxide, NO_2). Secondary pollutants form in the environment from precursors that are emitted, at least in part, by NG devices.

An example of a secondary pollutant is ozone, which is formed in the atmosphere when reactive organic gases, NO_X , and sunlight are all available in sufficient quantities. Because NO_X emissions from NG appliances contribute to ambient ozone formation, it is possible that increasing NO_X may increase ozone formation (although that is not always the case, owing to the complex chemical interactions responsible for NO_X formation).

The concerns and metrics included in the list below have either been the focus of past studies or there is evidence to suggest that they may be relevant to the evaluation of IX impacts. Many can apply to pilot flames (when present) in addition to the main appliance burners.

3.1. Safety and Performance Concerns and Metrics

A variety of safety and performance concerns and metrics must be addressed when evaluating NG interchangeability:

Flame initiation/ignition is a basic safety and performance issue evaluated by direct testing.

Flame stability problems (such as lifting and flashback) are basic safety and performance concerns evaluated by observation. Partial lifting can increase unburned gas and other pollutant emissions.

Flame codes (developed by the American Gas Association) provide a semi-quantitative measure of observable deviations from ideal flame form; they indicate flame stability problems that are more minor, though in the direction of lifting and flashback.

Yellow tipping is an observable condition that is often indicative of incomplete combustion associated with CO emissions and soot production.

Flame lengthening may impair performance, be associated with increased pollutant emissions (for example, CO) when longer flames impinge on surfaces, and lead to material degradation. It may be evaluated by observation, catalogued with flame codes, or in some cases measured by component surface temperatures.

Flame temperature determines NO_X formation and in some cases impacts device performance; it is difficult to measure directly in most devices.

Pilot light stability, if applicable, is a basic safety and performance concern evaluated by direct testing.

Safety feature performance is a basic safety issue. Concerns and evaluation approaches vary for specific equipment and safety components.

Performance temperatures can be measured on component surfaces (for example, a heat exchanger), in a material being heated (for example, air for a furnace, water for a water heater, oil for a deep fat fryer), in the combustion exhaust, or other key locations. Equipment temperatures that are too high may accelerate wear; exhaust temperatures that are too low may lead to condensation followed by heat exchanger or exhaust system corrosion and failure. These are measured directly.

Accelerated equipment wear can impair performance and possibly cause premature failure leading to safety concerns. Such wear can result from higher temperatures and/or flame impingement (resulting from lengthening).

Device surface temperatures (such as the temperatures of externally exposed surfaces) are important considerations for consumer safety and can be measured directly.

Specific performance issues include outputs and metrics that are application specific. One example that has been found to be an issue is the appropriate level of cooking associated with a timed charbroiler.

Energy efficiency relates useful heat output to fuel heat input. The measure of useful heat output will vary by appliance.

Incomplete combustion causes higher CO, possibly higher direct NO₂, soot formation under some conditions, and potentially other pollutants (such as formaldehyde); measured CO, CO/carbon dioxide (CO₂) ratios, and unburned hydrocarbons are good indicators of incomplete combustion.

3.2. Air Pollutant Concerns and Metrics

Natural gas interchangeability can effect the emissions from residential appliances. The following emissions are of concern:

Carbon monoxide (CO) is a poisonous gas and an intermediate species in the fuel combustion process. It is emitted when incomplete combustion occurs as a result of insufficient air or if the flame impinges on a surface. It is of greatest concern for devices that exhaust directly to the indoors (such as cooktop burners) or that are improperly vented. Accelerated material wear (such as the cracking of a heat exchanger resulting from flame impingement) leading to improper venting is also of concern. Carbon monoxide emission limits, expressed as the CO exhaust concentration on a dry, air-free (daf) basis, are specified in ANSI Z21 tests for many residential appliances.

The ratio of CO to CO₂ (CO/CO₂) accounts for increased CO₂ emissions associated with use of gases having higher Wobbe numbers. In some cases the increased heat input and CO₂ output is accompanied by a proportional increase in useful work output; normalizing CO to CO₂ thus may provide a more meaningful indicator of CO increases.

Nitrogen oxides (NO_X) , including NO and NO₂, are important precursors to ambient (outdoor) ozone formation.

Nitrogen dioxide (*NO*₂) is a respiratory irritant and important primary indoor and neighborhood scale outdoor air pollutant.

Ultrafine particles (UFPs) are liquid or solid materials with aerodynamic diameters less than 100 nanometers (nm). In the context of gas appliance emissions, UFPs may be composed almost entirely of condensed organic compounds or contain a larger fraction of optically black carbonaceous material that is characteristic of soot. There is a growing body of research suggesting that UFPs present a significant human health hazard, yet the importance of the specific chemical composition and physical properties are still not well understood. As with other primary pollutants, any direct emission into occupied buildings is of concern.

Soot is typically used to describe carbonaceous particles associated with combustion. In the context of gas appliances, the particles may be measured in the exhaust gas stream or observed to deposit within the device. Soot is formed in fuel-rich regions of the flame. The presence of observable quantities of soot is generally indicative of substantially incomplete combustion. Soot deposition can affect performance; for example, by fouling heat exchangers. Soot is an important air pollutant for human health, regional visibility, and global climate.

Methane (*CH*₄) is a potent greenhouse gas with important implications for global climate; methane emissions may increase during partial flame lifting (as some gas moves around the flame) or if ignition is delayed.

Formaldehyde is a regulated toxic air contaminant that is known to be emitted from gas appliances as a product of incomplete combustion. The major concern is direct human exposure close to the source—that is, indoors or on neighborhood scales.

1,3-Butadiene and Acrolein are regulated toxic air contaminant that can be emitted as products of incomplete combustion, though it is unclear if they are emitted in substantial quantities from natural gas appliances; the concern is direct human exposure close to the source—that is, indoors or on neighborhood scales.

Molecular oxygen (O_2) , CO_2 , and relative humidity (RH) are important components of the exhaust stream that are needed to calculate other parameters such as percent excess air, CO exhaust concentrations on a daf basis, CO/CO_2 ratios, energy efficiency, and others.

4.0 Overview of Existing Interchangeability Studies

4.1. Development of Standard Multiple Index Approaches

Fuel interchangeability has been an issue for much of the history of gas-burning appliances. A great deal of effort was devoted to understanding and predicting interchangeability as the gas industry switched from locally produced town gases to natural gases in the 1930s. The key question was whether the substitute fuel would burn safely and reliably in existing equipment. This was initially determined by empirical evaluation (experimental observation). It soon became apparent that predictive tools would be useful.

The seminal works in gas interchangeability research are studies that developed indices that collectively address the fundamental issues of basic safety and reliable operation. The most widely used interchangeability indices in the United States were developed and described in two reports that are summarized later in this chapter (AGA Laboratories 1948a; Weaver 1951). The indices consider fundamental combustion phenomena, basic principles of gas appliance design, and empirical data from large numbers of experiments conducted with varied fuels. The multiple indices have been summarized and discussed in a number of reviews (Halchuk-Harrington and Wilson 2006; Harsha et al. 1980; Kuipers 2005; Williams 2006).

An important feature of the AGA and Weaver index methods is that they are designed to predict burner performance with a potential *substitute* gas assuming acceptable performance, with some *adjust* gas as a requisite point of reference. Each index is intended to evaluate a specific aspect of performance, as summarized in Table 1.

Index limit values are derived from experiments with real burners. Limit values are intended to be applicable to the general population of appliance burners and therefore should be evaluated for burners or appliances that are most sensitive to gas quality. Because the appliance population changes over time and can vary geographically, it becomes necessary to conduct experiments to verify the suitability of limits developed from testing with a different population of appliances. The concept of a *limit gas* is also important. Limit gases set the bounds of acceptable performance for a given effect or metric.

U.S. and international index approaches developed through the 1970s have been catalogued (Harsha et al. 1980). The approach that has been used for IX evaluation in the U.K. for the past two decades is summarized by Dutton (1984).

4.2. Studies Focusing on Local Gas Quality Limits

The multiple index approaches developed by the AGA and Weaver have been used as standard IX evaluation tools up through the present time. However, it has long been recognized that the limit values suggested in the original studies need to be re-evaluated in light of burner and appliance technology developments and the specific gas compositions being considered for interchange.

Table 1. Summary description of AGA and Weaver interchangeability indices

Method	Index Name (Symbol)	Gas properties and other factors in calculation	
AGA	Flashback (I _F)	Wobbe number (WN); lifting constant	
AGA	Lifting (I _L)	WN; lifting constant; air requirement for stoichiometric combustion	
AGA	Yellow tipping (I _Y)	Stoichiometric air requirement; WN; yellow tip constant; percent inert components and O ₂ in fuel	
Weaver	Heat input rate (J _H)	Ratio of WNs	
Weaver	Primary air (J _A)	Stoichiometric air requirement; index is equal to J _H	
Weaver	Flashback (J _F)	J _A ; flame speeds	
Weaver	Lifting (J _L)	J _A ; flame speed; percent O ₂ in fuel gas	
Weaver	Incomplete combustion (J _I)	J _A ; average hydrogen to carbon ratio of fuel molecules; empirical fitting constants	
Weaver	Yellow tipping (J _Y)	J _A ; labile carbon atoms in fuel	

Many studies have been conducted with the objective of applying and/or updating the AGA or Weaver index limits to set local or regional gas quality limits. Local IX evaluations were often motivated by the availability of new supply streams having properties that differed from gas historically received and distributed in an area, or by the need to use peak shaving gases with different properties than regular pipeline supplies. Examples of this type of study include the evaluation of potential refinery gas use by the Public Service Gas & Electric Company (PSE&G, New Jersey) (Kelton 1971, 1978), and incorporation of higher heating value natural gas from Wyoming pipelines into the Colorado distribution system (Scott 1978). Several studies in the 1970s examined the impact of planned or actual introduction of LNG via new terminals in Elba Island, Georgia (TIAX 2004a), Cove Point, Maryland (Steinmetz 1979), and Everett, Massachusetts (Rossbach 1979; Steinmetz 1979). In almost all cases, the objective of these studies was to set gas quality limits appropriate to the local situation, that is, considering local historical gas quality and existing equipment in the local service area. Gas quality limits can be, and were, expressed in terms of one or more of the standard IX indices, directly in terms of gas properties (heating value or Wobbe number), or as a specification on the required mixing or dilution of the new gas supply with either domestic NG or an inert component (e.g., nitrogen (N_2) , CO_2 , or air).

The studies followed similar approaches, often starting with a comparison between calculated index values and previously defined AGA and Weaver limits; this provided a preliminary IX assessment for a potential substitute gas. Most of the studies included testing of common appliances, in some cases removed from homes in the service area. Several of the studies also included appliances thought to be specifically vulnerable. One of the key features of these studies was a focus on a core set of IX considerations, primarily flame stability (lifting) and CO. Several of the studies included testing of as-received units and simulation of problem conditions (such as improper primary air adjustment, burner misalignment) or other operational problems that could make appliances more prone to flame stability and CO problems, and thus, potentially more sensitive to IX problems.

Documentation for these locally targeted studies varies greatly in availability and level of detail. Some of the analyses were documented for the purpose of dissemination, typically via AGA

operations conferences and similar venues. Other studies are documented only in the reports submitted to the project sponsor or through internal company reports; the majority of these reports are not readily available to the public, although some are shared privately among industry experts.

Included in this group are two recent studies conducted by the TIAX consulting company in support of new activity at the Elba Island and Cove Point LNG receiving terminals (TIAX 2003, 2004a). These are well-conceived studies that contribute substantially to the base of currently relevant information on IX for residential appliances. They are included in this section because their objective was the determination of local gas quality limits, their scope was limited to the conventional concerns of flame stability and CO emissions, and documentation of the work is limited to a summary description of methods and results. At least one of the reports (TIAX 2004a), commissioned by Shell Trading, is being made available to "all interested parties" according to a Shell representative on LNG issues (Kuipers 2006a). This report includes summary descriptions of several earlier studies that are not readily available to the public. Another recent report by TIAX summarizes a study done for Washington Gas Light (TIAX 2003). A scanned (and in places illegible) version of this report is available through the Federal Energy Regulatory Commission (FERC) archives.⁵ A fully legible version was obtained by request from Edgar Kuipers of Shell NA LNG (Kuipers 2006b).

Finally, this section includes brief summaries of IX tests conducted on two furnaces pulled from residences (Suchovsky 2005; TIAX 2004b).

Recent reviews of IX issues make reference to several additional studies that are not reviewed here because no documentation could be obtained. In the executive summary of a recent study sponsored by the Southern California Gas Company (SCG 2005), reference is made to "extensive testing in the laboratory and field in the mid 90's" that involved comparisons between measurements and IX index calculations and the study of gas quality effects on efficiency and NO_X emissions. Despite requests to appropriate SCG representatives, no reports or other documentation of the earlier work could be obtained for this review. Xcel Energy of Colorado has been conducting laboratory and field evaluations of IX issues, with specific focus on device performance at altitude (Halchuk-Harrington 2006). Documentation about this work is being prepared but was not yet available as of late September 2006. A study conducted for the Commonwealth Gas Company is cited by industry experts and some summary documents (NGC+ 2005) in support of the point that many in-use appliances are already operating in a compromised manner and thus may be very sensitive to any gas quality change; however the report is not publicly available (Kuipers 2006c).

4.3. Systematic Studies of Natural Gas Interchangeability

Another group of studies are those designed to significantly advance understanding of gas interchangeability for residential appliances by examining (a) a more extensive collection of adjust and substitute gases, (b) new appliance technologies, and/or (c) potential IX impacts that had not previously been studied. A key feature of the studies included in this last group is that clear documentation exists and is available to the public; the degree of this availability is noted

⁵ Docket RP01-217-003 (7/16/2003); Accession number 20030722-0264; pp. 28–57.

below. Included in this section are the only two studies that the research team could find in the archival literature that deal specifically with gas quality impacts on emissions and performance of residential appliance burners.

Griffiths et al. (1982) systematically studied the effect of gas quality variations on performance and emissions of modern residential gas appliances. The objectives were to first define nationally relevant standard adjust and limit gases for use in IX testing, then to conduct extensive testing to build a database of interchangeability information for contemporary appliances. In addition to the standard metrics of flame stability and CO production, this study examined energy efficiency and included measurement of NO_X emissions. GTI researchers Johnson and Rue (2003) studied new appliances operated with three relevant adjust natural gases and six simulated LNG blends. A key feature of this work was the attempt to relate standard IX index values to quantitative performance and pollutant emissions measurements.

The Southern California Gas Company (SCG) conducted an experimental study that focused on gas mixtures having properties that were directly relevant to then-current local tariff limits (SCG, 2005). The broad value and relevance of this study derives from the inclusion of a wide range of appliance technologies (including several low-NO_x burners), the extensive range of effects examined and the publicly available documentation of methods and results. A similarly well-documented and extensive group of studies was commissioned by the U.K. Department of Trade and Industry (DTI) (Teekaram et al. 2005; Williams et al. 2004; Williams et al. 2005). The methods and results of these studies offer insights to the U.S. situation, even though many of the specific appliances tested in the U.K. differ from those in the United States.

A very limited number of studies examining gas interchangeability have appeared in the archival literature. Jones and Leng (Jones and Leng 1996) examined a pulse combustion room heater for a range of fuel flows and compositions. Ko and Lin (2003) examined performance, including energy efficiency, and emissions of a range-top burner with two NGs: a low and a high HV case.

4.4. Pollutant Emissions from Natural Gas Appliances

Measurement of pollutant emission rates from natural gas appliances was a focus of research in the 1970s and 1980s. Data on emission rates of CO, NO_X, fine particulate matter mass, methane, and formaldehyde that was available through the early 1990s have been reviewed (Traynor et al. 1996). In subsequent work, formaldehyde emission rates for five Australian domestic appliance burners are reported as a function of heat input and primary aeration (Ashman and Haynes 1996). This paper and earlier studies (Ashman et al. 1994; Stubington et al. 1994) experimentally examine the mechanisms that lead to pollutant emissions in production appliance burners. The chemical composition (Hildemann et al. 1991; Rogge et al. 1993) and the mutagenicity (Hannigan et al. 1994) of fine organic aerosol (particulate matter) emitted by residential gas appliances has been reported, and a recent study examined the contribution of natural gas emissions to the overall mutagenicity of ambient organic aerosol (Hannigan et al. 2005). Several studies in recent years have reported ultrafine particle emissions and emission rates associated with cooking on both gas and electric ranges (Dennekamp et al. 2001; Fortmann et al. 2001; He et al. 2004; Long et al. 2000; Wallace et al. 2004). Although these studies generally do not include operation of the appliance without the confounding factor of food preparation (confounding for the purpose of attribution of pollutant emission directly to the appliance

burner), it is clear from comparisons among specific cooking activities and between gas and electric appliances that the natural gas burners are themselves a major source of ultrafine particles. An ultrafine particle emission rate has been reported for a propane gas stove operated without a cooking load (Afshari et al. 2005). One study reported ultrafine particles being emitted into the living space of a home when a vented gas clothes dryer was used (Wallace 2005). Another recent study reported indoor levels of CO, NO₂, and polycyclic aromatic hydrocarbons resulting from use of an unvented natural gas fireplace (Dutton et al. 2001).

4.5. Prediction of Interchangeability from Combustion Fundamentals

Some gas interchangeability concerns have been examined by analysis of fundamental combustion parameters. The key parameters and basic effects are reviewed cogently by Kuipers (2005), and several effects have been studied in more detail by Levinsky (2004, 2005).

5.0 Summary Reviews of Key Interchangeability Studies

5.1. Development of Standard Multiple Index Approaches

5.1.1. AGA Bulletin 36 (AGA Laboratories 1946)

American Gas Association Laboratories conducted extensive laboratory testing with a specialized designed and constructed standardized burner and 18 contemporary appliance burners to determine the interchangeability of other fuel gases to supplement or substitute for natural gases (AGA Laboratories 1948a). Supplemental gases included mixtures of coke oven gas, producer gas, butane, reformed butane, blue gas, and various inert gases. The study included only three gases of relevance to natural gas IX concerns:

- A "high Btu natural gas" composed of 83% methane, 16% ethane, 0.5% CO_2 , and 0.5% N_2 (Heating value (H) = 1115 Btu/scf, Wobbe number (W) = 1394).
- A "high methane natural gas" composed of 94.5% methane and 5.5% inerts ($CO_2 + N_2$) (H = 959 Btu/scf, W = 1284).
- A "high inert natural gas" composed of 71.4% methane, 14% ethane, 1% propane, 0.5% CO_2 , and 13.1% N_2 (H = 1000 Btu/scf; W = 1201).

The appliances tested were two gas ranges, a floor furnace, an automatic storage water heater, a radiant heater, a vented circulator, a refrigerator, a range top burner, an impinging jet burner, and the AGA test burner. Burners were tuned to operate on one of the adjust gases, then used with 100% of each substitute gas. Appliance burners were tuned to give percentages of primary air between 40% and 80% of the amount theoretically required for complete combustion. Flames were observed to diagnose flashback, lifting, and/or yellow tipping. Carbon monoxide was measured but not used in the determination of index limits. If combustion was unsatisfactory at 100% substitute gas, the gas was diluted with adjust gas until combustion was acceptable.

The ultimate result of this seminal study was the development of three performance indices with associated limit values for acceptable interchangeability. These indices were intended to predict the likelihood of yellow tipping, lifting, and flashback when substituting one fuel gas for another.

The AGA indices are explained and discussed in detail in several existing reviews that are in the public domain (Halchuk-Harrington and Wilson 2006; Harsha et al. 1980; Kuipers 2005).

5.1.2. U.S. Bureau of Mines (Weaver 1951)

A second and related set of interchangeability indices was developed by Elmer R. Weaver of the U.S. Bureau of Mines (Weaver 1951). The objective of the Weaver study was to expand and improve the multiple index approach of AGA Bulletin 36. The scope of analysis was expanded to include a range of adjust gases, including coke oven gas, carbureted water gas, producer gas, blue gas, and mixtures of these gases; this contrasts with the earlier AGA work that focused on appliances adjusted for natural gases only. Weaver further expanded IX analysis through explicit consideration of incomplete combustion (J_I), as indicated by carbon monoxide formation; the earlier AGA study indicated that incomplete combustion was not a concern when the three AGA index limits were satisfied. Weaver sought to improve upon the AGA indices and thus developed new indices for lifting (J_L), flashback (J_F), and yellow tipping (J_Y). Weaver further included indices for heat input (J_H = ratio of Wobbe numbers for substitute and

adjust gas) and air supply (J_A) requirements. The Weaver multiple indices are based on analysis of data from Bulletin 36 and analogous studies in which appliance burners were adjusted to fuels other than natural gas; the latter are described in AGA Research Reports 1106A–1106D (AGA Laboratories, 1948a, b, 1949a, b). Weaver makes a clear presentation of the basis for the new index values and convincingly demonstrates their ability to reproduce the observations regarding acceptable and unacceptable burner performance in the AGA tests. There is one critically important point to note about the Weaver paper: specific index limit values presented for lifting and yellow tipping were developed from analyses of test data in which burners were adjusted with coke-oven gas (AGA Research Report 1106-A [AGA Laboratories 1948a]). This analysis was presented as an example and should not be construed as applicable to other adjust gases (such as natural gas).

5.1.3. Dutton 1978–1984

The approach used to set U.K. interchangeability guidelines is presented in a series of papers by Dutton (Dutton 1978; Dutton and Gimzewski 1983; Dutton 1984; Dutton and Wood 1984; Dutton and Souchard 1985). Dutton (1984) summarizes the approach, which specifies limits for a lifting index (LI), incomplete combustion factor (ICF), and "sooting" index (SI) for natural gases and considers flashback for gases containing hydrogen. Dutton's IX guidelines are based on extensive testing of actual appliances using many gas mixtures. Most tests were done with two to four component gas mixtures containing methane plus some combination of propane, hydrogen, and nitrogen. A substantial number of validation tests were done with gases having additional or different non-methane hydrocarbons (NMHC) and inert components.

Gas quality is characterized along three axes: (1) Wobbe number (representing the rate of energy flow to the burner), (2) percentage of propane plus inert constituents (N_2 and/or CO_2), and (3) percentage of hydrogen. The second category (NMHC + inert) is important for estimating the sooting effect of higher hydrocarbons. For natural gases the index space is two-dimensional (no hydrogen [H_2]). The lower-bound Wobbe limit is set to avoid lifting. Incomplete combustion factor is controlled primarily through an upper Wobbe limit with a small effect of NMHC + inert fraction. The sooting limit incorporates both factors. Each limit was determined by testing of an appliance type that was deemed to be the most sensitive to the effect being studied.

Lifting experiments examined 30 cooker hob (cooktop) burners. Lifting was assessed using a flame stability scale of 0–5. Results were averaged for all appliances tested for each gas. The G20 adjust gas (pure methane) had an average lifting index of about 0.6, indicating that some appliances had imperfect flames even when operated with the adjust gas. The recommended lean limit was a Wobbe number of 47.3 megajoules per cubic meter (MJ m⁻³) (~1270 Btu/scf).

Incomplete combustion factor was examined with eight instantaneous water heaters, but Dutton comments that "anything with a closed heat exchanger could probably have been used." The ICF considers the increase in CO/CO_2 when an appliance is operated with gas provided at 100%–120% of the nominal rating (that is, up to 20% over-fired). The trend for each test gas was compared to the trend for the reference gas. The values increase sharply with Wobbe number and secondarily with fraction of NMHC + inert. Incomplete combustion factor was studied with 52 mixtures containing methane in combination with propane, hydrogen, and/or nitrogen, and 27 mixtures containing varied quantities of CO_2 , ethane, propane, and butane.

Sooting was studied with four gas fires. Fewer devices were used to evaluate this effect because of the longer time required for the tests. Devices were modified to allow primary air to be controlled and measured. Following heating to steady state, the primary air was reduced in increments and the device run for two minutes to check for soot deposition. Soot index is the aeration that first gives soot, divided by the previously measured natural aeration. As above, all appliance tests were averaged for each gas mixture. Ninety gases having four components each and 30 more gases having some additional component were tested.

5.2. Studies Focusing on Local Gas Quality Limits

5.2.1. Public Service Electric & Gas (New Jersey) (Kelton 1971)

The Public Service Electric & Gas Company conducted an analysis to determine whether refinery gas from the Esso Bayway Refinery could be mixed with natural gas and ,if so, at what limit (Kelton 1971). They also examined the amounts of oil gas and propane-air that could be blended with the mixture of refinery gas and natural gas. To assess interchangeability, they compared heating value, specific gravity, Wobbe number, calculated Weaver indices, and the Knoy⁶ formula. The report deals principally with the Weaver interchangeability indices. It also synthesizes and relates these results to experimental measurements of flame speed and flame stability on test burners. In this study, IX was evaluated entirely on the visually observable (yellow tipping, lifting, and flashback) and calculable (Weaver indices) metrics. Both refinery and oil gases contain substantial amounts of H₂ and unsaturated hydrocarbons (HC). The refinery gas that was found to be most suitable had 16%–20% H₂ and 46%–57% unsaturated HC. The study did not include measurements of pollutant formation.

The single result of interest to the current review is that the limiting IX consideration in this study was yellow tipping. It is noteworthy that, even for these gases containing substantial amounts of H_2 , flashback was not a critical concern.

5.2.2. Elba Island Studies 1974–1978 (TIAX 2004a)

Several IX studies were conducted in connection with the opening of the Elba Island, Georgia, LNG terminal in 1978. Information about these studies is summarized in the final report of a recent study associated with renewed activity at the Elba Island terminal (TIAX 2004a). The original studies were conducted by (1) American Gas Association Laboratories (AGA Labs) for the Southern Energy Company, now Southern LNG, (2) Atlanta Gas Light Company (AGLC), and (3) Alabama Gas Corporation (AGC). Each of the studies included testing of appliances with a domestic NG and an Algerian LNG expected to be imported to Elba Island. Test gases and appliances are listed in Table 2. The studies examined flame stability (for example, lifting) and incomplete combustion (as indicated by CO production and yellow tipping). Appliances were generally tested for a range of primary air settings, including marginally acceptable performance with the adjust gas. The TIAX summary suggests that one common goal of these studies was to inform the need for, and provide guidance about, in-service appliance adjustments.

⁶ The Knoy index is calculated as $(H-175)s^{0.5}$ where H is heating value and s is specific gravity. The factor of 175 is the assumed heating value of the primary air and gas mixture in the burner head. See Harsha et al. (1980).

Table 2. Studies conducted in 1970s for Elba Island activation (TIAX 2004a)

Study ID	Appliances	Test Gases ¹	Approach & Metrics Notes
AGA 1974, Sponsored by Southern Energy Co. (now SLNG)	Commercial convection oven; Hotel range; Deep fat fryer; Bake oven; Water heater; Room heater (vented); Dryer; Forced air furnace; Residential range	Adjust: Domestic NG (H = 1036, W = 1354); Test: Algerian LNG (H = 1189, W = 1457)	- Set to yellow tipping limit with DNG, operated on LNG; - Set to lifting limit on LNG, operated with DNG; - Examined ignition, flame quality (flashback, lifting, yellow tipping), primary air injection rate, and CO.
Atlanta Gas Light 1975	Radiant heaters (20); Vented circulators (2); Range (3); Water heater (2); Gas light; Refrigerator; Dryer; Grill; (Appliances tested as received from Savannah homes)	Adjust: Domestic NG (H = 1030, W = 1349); Test: Algerian LNG (H = 1182, W = 1453)	- Examined ignition, flame quality (lifting, etc.), and CO.
Alabama Gas Corp. 1978	Range, Water heater, Furnace, Space heater	Adjust: Domestic NG (H = 1185, W = 1453; Test: Algerian LNG (H = 1185, W = 1453)	- Examined ignition, flame quality (lifting, etc.), and CO; - Examined switching from LNG to NG (lifting issue); - All tests conducted with properly adjusted appliances.

¹ Test gas properties are heating value (H) and Wobbe number (W), in units of Btu/scf.

Results from these studies that inform current IX concerns are summarized below.

Flame stability and quality. No fundamental operability problems (such as ignition or flame stability) were reported. The TIAX report states that lifting was not a problem in almost all cases when devices adjusted to the LNG then operated on the NG. The exception was that 4 of the 14 burners tested by the AGA exhibited lifting problems when operated cold with primary air shutters open to the LNG lifting limit. The lifting resolved within 2 to 5 minutes as the burners warmed and could be eliminated with a reduction in primary air. Flashback was not observed. Flame lengthening was observed for appliances adjusted to NG and operated on simulated

LNG. In the AGA study, yellow tipping was observed on 8 of 18 burners adjusted to the yellow tipping limit of the NG adjust gas then operated using the LNG blends without device readjustment. There was no evidence of carbon deposits associated with this yellow tipping.

Carbon monoxide (CO). Only a few of the appliances tested showed CO sensitivity to LNG. One of three furnaces tested by AGA labs had sharp CO sensitivity when air shutters were set to produce a soft flame with NG; sensitivity was greatly reduced when primary air was reset to produce a normal flame with NG.

Sensitive technologies and designs. In the AGC study, flame lengthening and yellow tipping could not be eliminated for a non-premix range pilot, and flame lengthening of a water heater pilot interfered with secondary air for the main burner. As a result, it was recommended that special attention be paid to service of non-premixed pilots or main burners. The AGLC study found that a high percentage of radiant heaters emitted high levels of CO on both NG and LNG. The Saturn burner on the water heater tested in the same study had high CO on the overfire test. The AGC study noted the sensitivity of appliances with non-premix pilots and unvented space heaters. Elongation of the pilot flame of the water heater interfered with secondary air for the main burner. The water heater also had a fixed primary air burner that required changing of orifices ("re-orificing") for air adjustment.

In-use appliance adjustments. Indicative of the mindset that apparently prevailed at the time, all of these studies suggest the potential use of appliance adjustments (including in some cases changing of orifices) as a strategy for accommodating gas quality changes. Such an approach was much more feasible at that time, because the utilities employed large numbers of service technicians who were routinely involved in new appliance installations and thus had greater access to appliances already installed. The recommendation was that a neutral flame adjustment with either domestic NG or the LNG would accommodate switching to the other gas blend.

5.2.3. Baltimore Gas & Electric (Maryland) (Steinmetz 1979)

This study reports on the steps taken by BG&E to prepare for and mitigate problems associated with distribution of LNG (received at Cove Point) starting in 1978. As a preliminary analysis tool, BG&E used AGA and Knoy indices to assess potential impacts of substituting Algerian LNG from the Cove Point terminal ($H = 1120 \, \text{Btu/scf}$, wet) for the domestic NG ($H \sim 1010 \, \text{Btu/scf}$, wet) common to the service area at the time. Results suggested that substitution could lead to yellow tipping but not lifting or flashback. In an interesting contrast to current thinking, Steinmetz asserted that some level of impact and the associated increase in service calls would be acceptable.

In further considering possible effects, Steinmetz quotes a 1970 study by AGA Laboratories that concluded "Satisfactory performance should be attained in domestic gas appliances when the LNG is substituted for pipeline natural gas. No readjustment of the appliance should be required provided the appliance has a reasonable primary air setting to begin with" (quotes by Steinmetz; no citation provided). Steinmetz then notes that "tests performed by Baltimore using simulated Cove Point LNG on various appliances confirmed this conclusion." No further details of these BG&E tests are provided.

Despite the results noted above, BG&E recognized two classes of appliances vulnerable to gas quality changes: (1) devices that are dirty or in otherwise poor condition, and (2) devices having

"burners with limited combustion flexibility due to lack of primary air and/or input adjustment." A Saturn water heater burner that incorporated a small pilot into the main burner was identified as an example of such a technology. Physical testing demonstrated that operating this burner (B143 Saturn) with LNG produced carbon deposition on the underside of the storage tank, but a replacement model B138 burner yielded acceptable performance.

Additional measures were taken to prepare for introduction of LNG. Starting in October 1976, field service technicians were instructed to use a "sharp" flame adjustment with domestic NG. A field study was conducted by qualified technicians to assess potential problems with the inservice appliance population receiving LNG. Approximately 1000 surveys each for ranges, water heaters, and "house heaters" found that as many as 10%–20% of ranges, 10%–15% of water heaters, and 5%–10% of house heaters could require service calls based on their condition. BG&E also pro-actively replaced the problematic Saturn burners, starting with 3142 units that had been sold by the utility, then 5088 additional units identified through canvassing of more than 500,000 customers. A follow-up effort to contact 88,000 additional dwelling units that were missed in previous campaigns was planned at the time of the report.

Liquefied natural gas was introduced in three phases as BG&E evaluated in-use equipment response with the following metrics:

- Quantifying service call receipts for comparison to previous years at the same time.
- Filing of LNG service survey tickets by technicians suspecting that a problem was associated with the LNG introduction.
- Monitoring of CO and CO₂ on all appliances at 100 randomly selected premises and some industrial equipment, to quantify "baseline" conditions and do follow-up evaluations during each phase of LNG introduction.

During Phase I (June 15–22, 1978), the heating value of delivered gas averaged 1070 Btu/scf (wet). Since no adverse effects were observed, Phase II proceeded with distribution of 1100 Btu/scf (wet) gas on July 24–26, 1978. Gas distributed during Phase III (July 27 through August 7, 1978) ranged from 1113 to 1131 Btu/scf (wet). During this period, domestic and commercial calls for service rose 12%, odor complaints rose 31%, and leak reports increased by 10% over the same period during the previous year. It is speculated that an unrelated reportable incident that occurred on July 28, 1978, and garnered publicity may have biased these reports.

Somewhat widespread problems were observed on three types of burners during the Phase III LNG introduction. The first involved range top burner pilot lights. BG&E first received complaints that pilots were "too high," had "carbon odor," or were causing "carbon deposits." Field service personnel confirmed a real adverse effect that accounted for one-fourth to one-third of their service calls during this period. The baseline monitoring program found that a significant percentage of the ovens were "producing carbon monoxide," which for many was corrected by a "simple air adjustment." During Phase III, the percentage of ovens producing CO "increased markedly." In response to this observation, company service technicians were instructed to adjust the oven on every premise visited for any reason. A planned follow-up program was to target homes suspected of using their ranges as residential heaters. The third problem involved a conversion burner, used as original equipment on a hot water boiler, which was known to have marginal performance on domestic NG. Excessive CO was found on four

such units tested while using Phase III LNG. Repairs of 182 such units that could be identified involved reducing the fuel/heat input rate by approximately 30%.

5.2.4. Public Service Company (Colorado) (Scott 1978)

This study was conducted by the Institute of Gas Technology (IGT) for the Colorado Interstate Gas Company; testing was performed at the Public Service Company (PSC) laboratory in Denver, Colorado.

The objective of this study was to evaluate whether Wyoming pipeline gas (H = 1049 Btu/scf, W = 1329) could be supplied to the Denver area, which historically had received gas of lower heating value (H = 993 Btu/scf, W = 1220). The study examined Wyoming gas diluted with 5% or 10% dry air and with 60% or 85% of the ethane removed. The potential substitute gases were first evaluated using AGA and Weaver index calculations, then by testing on three appliances: a kitchen range, a duct furnace, and a water heater. Testing was performed with appliances adjusted correctly, then improperly adjusted by (1) reduction of primary air (where possible), (2) increasing manifold pressure 25% above suggested value, and (3) improper adjustment of range pilot. Interchangeability was based on acceptable flame quality (no flashback, lifting, or yellow tipping), carbon monoxide emissions below ANSI standards for the tested appliances, and whether measured heat input was within tariff limits of ±6% maximum (Btu/hour (h)) as rated by PSC. The properly adjusted appliances achieved acceptable performance (stable flames, CO within ANSI standards) for the Wyoming gas blended with either 5% or 10% air, or with 60% or 85% ethane removed. Use of unaltered Wyoming pipeline gas yielded high CO (760 parts per million [ppm] air-free) in the correctly adjusted water heater; this was associated with a reduction of primary aeration to approximately zero. Poorly adjusted appliances had CO above ANSI limits in some of the tests with each substitute gas (Wyoming unaltered, diluted with air, and with ethane reduced).

5.2.5. Public Service Electric & Gas (New Jersey) (Kelton 1978)

This conference paper presents limits for Weaver indices that were determined for the PSE&G service area based on lab and field testing programs. The paper does not provide details of the testing programs but does identify and explain differences between their proposed limits and those originally proposed by Weaver. Much of the discussion relates to use of refinery gas as a standard supplement and use of oil gas and propane-air mixtures for peak shaving. The paper briefly mentions an "initial investigation... in anticipation of the receipt of Algerian LNG supplies into our system," which found that incomplete combustion and heat input would be the primary concerns. Flashback was identified as the limiting factor for oil gas, refinery gas, and other mixtures containing substantial amounts of hydrogen. For propane-air peak shaving blends, yellow tipping was the limiting concern. The paper notes that the Weaver indices and limit values were developed for atmospheric injection burners and thus may not be appropriate for other types of burners. For example, PSE&G testing found that the Weaver limit for flashback had to be revised based on behavior of target type pilot burners. The PSE&G Weaver index limits for heat input, lifting, flashback, yellow tipping, and incomplete combustion were given as $J_H = 0.95-1.03$, $J_L > 0.64$, $J_F < 0.26$, $J_Y < 0.30$, and $J_I < 0.05$, respectively. These guidelines allowed a maximum of 50% Algerian LNG (H = 1133 Btu/scf; W = 1420) to be blended with domestic gas (H = 1020 Btu/scf; W = 1339) to satisfy the heat input criteria.

5.2.6. Brooklyn Union Gas (New York) (Rossbach 1979)

In the early 1970s, Brooklyn Union Gas (BUG) contracted to receive LNG through the Distrigas Terminal in Everett, Massachusetts, via a cryogenic barge making a round trip every 3.5–4 days. BUG tested simulated gas mixtures with H = 1100 Btu/scf and various percentages of air. Tests were done on a limited number of appliances, including ranges, house heaters, water heaters, gas refrigerators, and space heaters. AGA index values were calculated using the high methane adjust gas from the AGA tests, and limit values were found to be $I_L < 1.02$ and $I_Y > 0.96$. No flashback was observed, so they used the AGA limit of I_F < 1.18. With these limits, they developed guidelines for air dilution of LNG. The report includes a figure showing the amount of air dilution needed for LNG having varying heating values. No air dilution was needed for LNG with heating value in the range of 1017 to 1080 Btu/scf. In addition to index metrics of lifting, flashback, and yellow tipping, carbon monoxide was mentioned as a concern. However, it is not clear if CO emissions were measured or if yellow tipping was used as a surrogate measure. The objective of BUG was to minimize or completely avoid residential end-use impacts, recognizing that many appliances were poorly maintained. The misuse of gas cooking appliances for space heating was specifically noted as a major concern. In January 1974, six shipments of LNG were received and stored, then used for peak shaving. Subsequent to this, BUG received LNG from Cove Point blended with domestic gas.

5.2.7. Pacific Gas & Electric (CA) (Estrada Jr. 1996)

Pacific Gas & Electric conducted this study to "determine whether the limits prescribed by the AGA apply to a typical customer base in its service territory." The study included laboratory testing of 10 devices—4 ranges, 2 forced air furnaces, 2 wall furnaces, and 2 water heaters—selected to "represent the various ages, conditions, and design of appliances" typical of the PG&E service area at the time of testing (1995). Devices were obtained, and testing was done at the PG&E Appliance Training Facility. Devices were rated and tuned for an adjust gas with H = 995 Btu/scf, then operated with various gas blends designed to identify lifting and yellow tipping limits. No information is provided about test protocols, but it is assumed that the flame characteristics were evaluated during steady operation. Yellow tipping and lifting flames were evaluated on a three-tier scale: excellent, average but acceptable, and unacceptable.

Flashback did not occur in any of the tests. The report states that CO was measured, and exhaust concentrations above 100 ppm CO were noted; however no CO results are reported. Similarly, the reports mentions but does not provide results for measurements of stack temperature and combustion efficiency. Burner ignition was reportedly evaluated and judged as acceptable if occurring within 4 to 5 seconds. The report includes no mention of unacceptable ignition behavior nor does it explicitly state that all appliances ignited within the allowed time.

The primary results presented were the heating values and calculated index limits of the gases for which lifting or yellow tipping were observed to occur for each appliance. These results were compared to the lifting and yellow tipping limit gases calculated with the 1988 edition of the AGA Interchangeability Program. The experimentally determined lifting limits were outside of the range allowed by the AGA program, that is, the AGA index limits were acceptably protective for lifting ($I_L \le 1.06$). By contrast, 7 of the 10 appliances—including 3 ranges, 1 water heater, and 3 furnaces—were observed to have yellow tipping with gas mixtures that were deemed acceptable based on the AGA limit for the yellow tipping index ($I_Y \ge 0.8$). Acceptable limits of maximum and minimum heating value gases—based on experiments—were reported

as 950 to 1040 Btu/scf; this is for an adjust gas with heating value of 995 Btu/scf. The analogous values of index limits are $I_L \le 1.06$ and $I_Y \ge 0.89$.

It is interesting to note that the adjust gas selected for this study had a heating value (995 Btu/scf) that was well below the reported average for the PG&E service area (1025 Btu/scf). It appears to have been selected as the midpoint of the range of heating values reported for that time (925–1080 Btu/scf).

It is also important to note that PG&E's initial selection of limit values was based on the "objectionable" criteria of the AGA. For in-use appliances, it is more appropriate to use the "preferred" values of $I_L \le 1$ and $I_Y \ge 1$. All test results would have complied with these limits.

5.2.8. Public Service Company of Colorado (PSCo) (Halchuk 1996)

In this conference paper, Halchuk provides an overview and brief history of PSCo use of air to reduce the Wobbe number of new supplies. The issue for Colorado was the incorporation of new domestic pipeline supplies having Wobbe numbers in the neighborhood of 1330 Btu/scf into a system that had developed around a supply stream having high nitrogen content and consequently Wobbe numbers in the low 1200s (Btu/scf). The paper briefly mentions company efforts to change the orifices in selected service areas, including Fort Collins in 1969 and a project in Vail Valley that was completed in 1995. The Vail project involved 4200 customers, required 16,000 labor hours over 4 months and cost \$1,500,000. The orifice changing projects revealed that many appliances were improperly adjusted; specifically, many were not adequately de-rated for elevation, leading to over-firing. The program thus resulted in improved appliance operation and a decrease in gas usage.

5.2.9. Cove Point / Washington Gas Light (Maryland/Washington, D.C.)

A major study was conducted to evaluate the range of LNG compositions and heating values, and the amount of N₂-dilution required for LNGs received at Cove Point to be distributed in the Washington Gas Light (WGL) service area. This study was initiated by the Cove Point steering committee, consisting of WGL, Dominion Gas, BP, Shell, and Statoil. The study was motivated by the return to service of the Cove Point LNG receiving terminal. The pilot phase of the study is reported in a conference paper by Rana and Johnston (2003), which is reviewed below. The full study is summarized in a bullet-point report prepared by the TIAX consulting group, who conducted the main study; this report is available by request (Kuipers 2006a).

5.2.10. Washington Gas Light (Maryland/Washington, D.C.) (Rana and Johnston 2003)

A conference paper (Rana and Johnston 2003) presents methodology and results for the pilot phase of the Cove Point/Washington Gas Light study including examination of gas quality variability, calculation of Weaver index limit values based on this variability, and pilot testing of three burners on two legacy appliances (cooktop and oven burners on a range, and a water heater).

The study first identified three typical LNG blends that were expected at the Cove Point terminal. The original operating plan called for a maximum heating value of 1138 Btu/scf for LNG arriving at the plant and a maximum of 1100 Btu/scf for revaporized LNG leaving the plant; N_2 dilution up to 4% would be used to achieve the reduction. One of the three blends (Tr) met the heating value limit while the other two (A and T) required dilution with 3.39% and

3.33% N₂, respectively. The pure (Tr) and diluted (A and T) LNG blends were considered for analysis.

Gas quality data for the service area that was going to receive gas from the Cove Point terminal was analyzed to quantify the variability to which the existing infrastructure had been exposed. The heating value of gas distributed through the Gardiner Road gate—which would be the largest single gate delivering revaporized LNG from Cove Point—was found to vary from 1030 to 1075 Btu/scf with an average of 1045 Btu/scf, and this range was found to be typical of other areas that would receive LNG. Limit gases having heating values of 1036 and 1066 Btu/scf were selected to encompass 85% of the days during the period studied. These limit gases were used to calculate Weaver index values assuming the worst case scenarios of an appliance adjusted with one of the limit gases, then operated with the other. With 1036 as the adjust gas and 1066 as the substitute gas, the standard Weaver limits for incomplete combustion ($J_I > 0$) and yellow tipping ($J_Y > 1.0$) were exceeded. When 1066 was set as the adjust gas and 1036 as the substitute gas, the lifting limit ($J_L < 1.0$) was exceeded. However, since these gases were assumed to be interchangeable based on operational experience, the index values obtained with this calculation ($J_I = 0.03$, $J_Y = 0.95$, and $J_L = 1.03$, rounded values) were designated as the appropriate limits.

Weaver indices for lifting, yellow tipping, and incomplete combustion were calculated for the three anticipated LNG blends (A, T, Tr), based on a 1036 Btu/scf adjust gas. Indices for the Tr blend were within the WGL-specific limits noted above. The A and T blends required N_2 dilution at 4.86% and 5.66% to meet these limits. According to this analysis, interchangeability could not be accommodated within the operating plan of 4% maximum N_2 -dilution.

The pilot phase concluded with an experimental investigation of burners on a conventional (storage) hot water heater, an oven, and a cooktop. Each was operated in a way designed to be most sensitive to the interchangeability challenge. The water heater burner was intentionally misaligned. The oven was operated with a primary air inlet in the most closed position. These two burners were adjusted using the 1036 Btu/scf gas. The cooktop burner was first set at the yellow tipping limit before being operated with pure and diluted LNGs. In all cases, acceptable performance was achieved by diluting LNG T with approximately 2%–3% N_2 .

Lifting was evaluated by increasing the manifold gas pressure (to above normal) and primary air to the cooktop burner to a point at which the flame was at the lifting limit with the adjust gas. The flame remained stable (no lifting) when the LNG with $5.39\%~N_2$ was substituted. These results suggested that even the revised Weaver index limits may be overly conservative.

The report contains interesting data concerning the temporal behavior of CO concentrations during water heater testing. The results demonstrate that emissions during much of the warm-up period were higher than at the 15-minute point at which official results were reported. Importantly, it appears that the cumulative emissions associated with each test gas do not necessarily scale with those measured at 15 minutes—that is, after the warm-up period.

5.2.11. Cove Point (Maryland) (TIAX 2003)

Following the pilot work, the Cove Point/Washington Gas Light study was expanded to include testing of a larger pool of appliances, including some units that were purchased new and others that were recruited from the service area (TIAX 2003). The same adjust gases (having

GCVs of 1036 and 1066 Btu/scf) were used. The LNGs selected for this phase of the study represented variability in heating value (1098 to 1143 Btu/scf), Wobbe number, and composition (specifically the ratio of ethane to propane) that is expected for LNG coming into Cove Point. The LNG blends were diluted with varying percentages of N_2 . Appliances were first set to conditions likely to cause sensitivity to CO emissions (for example, by mistuning, blocking flues or air vents) and tested with the higher heating value adjust gas and three LNGs diluted with N_2 . Next appliances were installed according to manufacturer specifications and tested on both adjust gases and the three LNGs diluted with N_2 . Additional tests were conducted on selected appliances with a fourth LNG diluted with N_2 .

In total, the test program included burners from six cooking devices (cooktops, ovens, and broilers), two space heaters, four furnaces, five boilers, and four water heaters. Interchangeability was determined by the following:

- Measurements of natural gas flow rates (for determination of heat input), CO, O2, CO2, and soot.
- Visual observations, photos and movies to assess flame characteristics.
- Calculation of Weaver interchangeability indices for incomplete combustion, yellow tipping, and lifting (J_L, J_Y, and J_L).

The objective was to achieve performance comparable to the adjust gas. For example, the limit for incomplete combustion for each test burner was determined by diluting the LNGs until CO emissions matched those measured when the burner was operated with the adjust gas.

The report presents summary findings for each impact studied. The major products of the study were (1) recommended levels of N_2 dilution for the specific LNGs examined in the study and (2) a set of limit values for the three Weaver indices that can be used to set N_2 -dilution levels for varying LNG supplies.

Incomplete combustion was evaluated by measurements of exhaust gas CO. The report offers a good summary of the operating modes sensitive to CO production (design features, non-uniform or off-design air fuel ratio, flame impingement) and CO release indoors (improper venting, lack of venting, cracked heat exchanger); selected appliances were tested on some of these modes to evaluate CO emissions under the most sensitive conditions. Thirteen of the appliances exhibited CO-sensitive behavior. Carbon monoxide emissions were reduced to or below the levels associated with use on the adjust gas for all appliances tested with the three simulated LNGs diluted with N₂ at levels of 3.7%, 3.4%, and 1.8%. These levels of N₂ dilution corresponded to a J₁ limit of 0.030 and produced overall decreases in average CO emissions from the group of test appliances.

LNG blends 1 and 2 required N_2 dilution at levels of approximately 3.5% to achieve yellow-tipping behavior similar to operation with adjust gas. The corresponding J_Y value of 0.119 was recommended as an appropriate limit. When LNG blends 3 and 4 were diluted with N_2 to achieve this J_Y limit, yellow tipping was acceptable but not reduced to the level observed with the adjust gas.

A recommended Weaver lifting limit was developed based on analysis and tests using the 1066 Btu/scf (GCV) as adjust gas and 1036 Btu/scf (GCV) as substitute. The amount of N_2 dilution of LNGs required to achieve this limit was calculated using the 1036 Btu/scf as adjust gas.

The recommended index limits of $J_I \le 0.030$, $J_Y \le 0.119$, and $J_L \ge 1.000$ correspond to N_2 dilutions of 3.5% to 4.7%, 3.4% to 5.3%, 1.6% to 3.3%, and 3.0% to 4.4% for the four LNG blends.

5.2.12. Elba Island / Southern LNG (TIAX 2004a)

In connection to the importation of LNG (via Elba Island terminal) to Southern LNG (SLNG) pipelines, SLNG sought input on possible changes to the tariff gas quality limits. SLNG asked TIAX to evaluate an upper Wobbe number limit of 1395 Btu/scf. The summary recommendation by TIAX was that SLNG instead should adopt tariff limits based on Weaver indices. To achieve these limits it was recommended that imported LNGs be blended with N_2 at levels of 0 to 2.3 percent by volume. This recommendation was based on a review of previous appliance testing including the studies conducted in the 1970s (see above) and a study commissioned by Southern LNG in 2001, which is described just below. The following Weaver index limit values were suggested: lifting, $J_L \geq 0.95$; flashback, $J_F \leq 0.08$; yellow tipping, $J_Y \leq 0.14$; incomplete combustion, $J_I \leq 0.42$; heat rate, $J_H 0.95$ –1.03.

SLNG Appliance Tests

In 2001, SLNG hired Arthur D. Little to test appliances for performance with revaporized LNG. Tested appliances included two unvented fireplaces, an infrared space heater, a blue flame space heater, an oven, and a flammable vapor ignition resistant (FVIR) water heater. Test gases included domestic NG (W = 1354 Btu/scf), and four LNG blends (W = 1380–1432 Btu/scf). Properly adjusted burners accommodated the varied gases with minimal impacts on CO. Improper adjustment of the oven burner and misalignment of the water heater burner led sharp CO increases when appliances were operated with the higher Wobbe LNGs.

Pulsed Furnace Test

Southern LNG asked TIAX to test a pulse combustion furnace because this technology had previously not been tested for gas interchangeability (TIAX, 2004b). Since this type of furnace is no longer marketed, an installed unit was identified. The device was an 80,000 Btu/h Lennox (model G14Q4-80). The unit was first tested on line gas in the residence where it had been operating; CO, O₂, manifold pressure, and flue gas temperature were measured in the field. Gas supply was measured in the field using the house gas meter. The furnace was subsequently installed in a TIAX laboratory and tested with four fuels: domestic line gas (Cambridge, Massachusetts), a simulated Nigerian LNG mixed with 2.3% nitrogen, simulated Algerian LNG diluted with 0.7% N₂, and a blend of domestic NG and simulated LNG to achieve a heating value of 1085 Btu/scf. The furnace had no problems with ignition or flame stability, and CO emissions with the burner operating in a warm stable mode were very low for all gases tested. A simulated blockage of the vent did not cause any change to CO emissions.

5.3. Systematic Studies of Natural Gas Interchangeability

5.3.1. American Gas Association / Gas Research Institute (Griffiths et al. 1982)

This study was initiated to support consideration of incorporating fuel flexibility evaluation into the Z21 series of ANSI appliance test protocols. The objectives were to first define nationally relevant standard adjust and limit gases for use in IX testing then to conduct extensive testing to build a database of interchangeability information for contemporary appliances. In addition to the standard metrics of flame stability and CO production, this study

examined energy efficiency and included measurement of NO_X emissions. AGA Laboratories conducted the experimental work, and Science Applications, Inc. analyzed the data for performance modeling.

Approach

Adjust and limit gases were developed based on analysis of existing information and results of a then-recent survey of natural and peak shaving gases being supplied throughout the United States. A typical adjustment gas (A) with Wobbe number and heating value "midway in the span" of those distributed in the field was selected, then AGA indices were used to develop lifting (L), yellow tip (Y) and flashback (F) limit gases for use in conjunction with this adjust gas (see Table 3). It is interesting to note that the initial F gas composition of 76% methane and 24% H_2 with AGA flashback index I_F = 1.20 (the Bulletin 36 limit) produced no flashback when used in a number of appliances. Additional testing was done with some field gases having characteristics similar to the selected limit gases and peak shaving gases.

Tested appliances included 14 tank water heaters (WH), 15 furnaces, 4 sets of range burners, 4 sets of oven/broiler burners, a clothes dryer, 5 boilers, a room heater, a deep fat fryer, and an infrared broiler. Burners were all atmospheric. WH burner types included circular stamped steel (horizontal and target-type), circular cast iron, cylindrical stamped stainless steel, and a "power burner." Furnace burners included bayonet-type stamped steel with slotted ports, circular cast iron with slotted ports, stamped steel in-shot burners, and a pulse combustion burner. Range top and oven burners were stamped aluminum circular and tubular steel. Boilers were stamped steel bayonet type or tubular, cast iron up-shot, or pulse combustion. The infrared broiler was a ceramic tile burner. Some, but not all burners had adjustable primary air. Not all appliances were used in all test systems. Though not specified, it is inferred that all appliances were new.

The primary evaluation involved rating and adjusting of appliances with one gas followed by operation with other gases without readjustment. Burners with adjustable primary aeration were tested at three settings appropriate to the metric; for example, yellow tipping was examined with (1) maximum aeration, (2) aeration at yellow tip limit of adjustment gas, and (3) aeration set at yellow tip limit of substitute gas. Analogous settings were used to study lifting. In flashback studies, primary air was set at wide open or reduced to eliminate flashback; performance was then determined with other test gases.

Because lifting depends on burner surface temperature and is most likely to occur with a cold burner, it was evaluated after 1 minute of operation from cold start. Adjustable burners were fired with stable flames and primary aeration was increased to obtain lifting flames; just prior to the 1 minute point, aeration was decreased just enough to eliminate lifting. Sampling of primary air was started at 55 and ended at 65 seconds.

Evaluation included measurement of CO, NO_x, O₂, and CO₂ during steady device operation, as specified by then-current ANSI protocols. These measurements were used to calculate exhaust pollutant concentrations on an air-free basis.

Table 3. Summary of experimental parameters in Griffiths et al. (1982)

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Appliances ¹	Test Gases ²	Metrics/Effects	Methods Notes
Tank water heaters (14) Central furnaces (15) Range burner sets (4) Oven/broiler sets (4) Clothes dryer Boilers (5) Room heater Deep fat fryer Infra-red broiler	Adjust (A), US typical: W = 1296, H = 1064; Lifting limit (L): W = 1179, H = 961; Yellow tip limit (Y): W = 1432, H = 1148 Flashback limit (F): W = 1062, H = 1061 (34% C ₁ , 19% C ₃ , 10% C ₃ H ₆ , 37% air) Some tests used NGs w/similar properties	Flame quality (lifting, flashback, yellow tipping); Index values; CO, NOx, O2, CO2; (NO/NO2 measured but not reported); Efficiency; Performance temperatures	A. IX combos to determine flame stability, CO emissions: - Rate w/L,Y, run A,L,Y; - Rate w/A, run L,Y; - Rate w/A, adjust prime air & run L,Y. Additional studies: B. Lifting; C. Yellow tip; D. Flashback; E. Burner/pilot operation; F. Completeness of combustion (CO); G. NO _X production; H. Thermal efficiency; I. Ignition system component temps.
			1

¹ Ages and conditions of appliances not specified; presumed to be new. Not all appliances used in each test sequence.

Results

The report itself offers the following summary of results: "Variations in composition of simulated natural and peak-shaving gases do not appear to noticeably affect efficiencies of residential forced-air furnaces, hot water boilers, water heaters, and ranges, or the temperatures of ignition-system components or appliance burners. Gas composition variation does, however, have a noticeable effect on other burner performance criteria and on the CO, CO₂, and NO_x emissions characteristics of the burners tested." Additional key results are organized below, according to the sections of the report.

Steinmetz (1989) notes the following summary results for this study: "(a) almost all equipment cannot be properly rated and adjusted on any one limit gas, then perform satisfactorily on other limit gases; (b) almost all equipment can perform satisfactorily when properly rated and adjusted on the mid-range adjust gas and exposed to any limit gas; (c) almost all equipment will fail to perform satisfactorily on one or more limit criteria when the limit gas is made more severe than the established index using the procedure in b."

² Properties given are for Wobbe number (W) and Higher Heating (Gross Calorific) Value (H), each in units of Btu/scf. In some tests, appliances were adjusted with one of the limit gases or another substitute gas.

A. Initial Studies of Gas Substitution. This study first examined a pair of gases that differed much more than those generally considered for interchangeability, with predictable results; when appliances rated for L gas were operated with Y gas (Wobbe ratio = 1432/1179 = 1.21), many had exhaust CO in excess of 800 ppm (10 of 17 tested with maximum or fixed primary air) and/or exhibited yellow tipping. Substitution of A gas in burners rated for L (Wobbe ratio = 1296/1179 = 1.10) had exhaust CO above 800 ppm in 2 of 16 appliances tested with maximum or fixed primary air supply, and two additional appliances had CO emissions increase by more than a factor of 3 relative to operation on the adjust gas. Similarly, substitution of Y gas in burners rated for A gas (Wobbe ratio = 1432/1296 = 1.10) produced CO above 800 ppm in 5 of 17 appliances tested with maximum or fixed air supply and led to substantial CO increases in 2 additional appliances. Yellow tipping did not always predict high CO, especially for tests with Wobbe ratios of 1.10. When rated with A gas and primary aeration set to a "reasonable" level, 19 of 31 appliances operated satisfactorily on all test gases. Four appliances had CO levels exceed ANSI limits (three with Y gas, one with all gases). Eight appliances exhibited yellow tipping on one or more gases. Three appliances exhibited lifting, but two of these did so by design (a deep fat fryer and a boiler). The authors concluded that a "gas substitution resulting in an input increase of about 10 percent does not appear to be unreasonable"; however, this subjective evaluation may not be considered to represent acceptable interchangeability by today's standards.

B. Lifting. The authors note that "very little, if any, lifting of burner flames occurred with the appliances as received, when operated with the A, L, Y, or H (flashback) gases. For the purposes of study, lifting was induced by rating appliances with smaller gas orifices and increasing gas manifold pressures much higher than used in practice to increase primary air injection." Using these extreme conditions, lifting limits were determined for six appliances with the limit test gases (A, L, Y, and H) and for two additional appliances with combinations of simulated field gases and limit test gases. The conclusion of the study was that "considering the accuracies of setting burner primary aerations at lifting limit values and of measuring primary aerations...the Bulletin 36 index appears to reasonably characterize lifting tendencies with gas substitutions."

C. Yellow Tipping. As noted above, yellow tipping was observed with the more challenging combinations of adjust and substitute gases and aeration setting. Yellow tipping was also studied with peak shaving, field gases, and methane. The authors concluded that the AGA Bulletin 36 limit provides a reasonable prediction of the behavior observed for the collection of appliances tested.

D. Flashback. Flashback was examined as a concern relevant to peak shaving gases, with the same objective of comparing the conditions at which flashback was observed in experiments with those predicted by the AGA flashback index. The conclusion was that the Bulletin 36 index "does reasonably characterize flashback tendencies of peak-shaving gases."

E. Burner and Pilot Operating Characteristics. Operation was checked using ANSI protocols for all appliances with test gases A, L, Y, and F. Performance was acceptable for ignition, pilot, and main burners in almost all cases. One exception was water heater L—which used a power burner to premix all combustion air—rated with gas A. The flame would not ignite for L and F gases when all four of the air shutters were open. When one of the four openings was blocked, all four of the test gases ignited and burned stably; however, CO was above standards for gases Y and F.

F. Completeness of Combustion. The purpose of this set of tests was to compare the relative effect on CO of gas substitution versus increasing manifold pressure. Appliances first were correctly rated with A gas and set with "reasonable" primary aeration (usually the maximum), then operated with Y gas. Appliances were then over-fired with A gas first as specified in the appropriate ANSI tests protocols (12.5% for the furnaces and range tops and 6.25% for the boilers and ovens), then the boilers and ovens were tested again at over-firing rates giving the same heat input as the yellow-tipping limit gas. The stated conclusion was that exhaust CO levels were similar when the degree of over-firing was similar to the change in fuel delivery rate with gas substitution (Wobbe ratio). While most of the data support this conclusion, Table 19 of the report indicates that Furnace B operating on the yellow tip limit gas (Y) had exhaust CO levels that were nine times as high as those observed during the over-firing test with adjust gas A.

G. Nitrogen Oxides (NO_X). The report concludes that "there does not appear to be consistent trends relating NO_X production to gas composition and/or primary aeration." The report (p. 124) observes that "usually NO_X levels were lower for a given gas at lower primary aeration," but this is not obvious from a quick review of the data in Table 20 of the report. NO_X levels were reported to be somewhat lower in pulse combustion appliances (Furnace L and Boiler E) and very low for IR burner (Broiler A). The NO/NO_X ratio varied with fuel variation. In the furnaces, most of NO_X was in the form of NO; with range-top burners NO_2 was a larger part of total NO_X .

H. Thermal Efficiency. Thermal efficiencies were calculated using applicable U.S. Department of Energy test protocols and analysis methods. Very small changes in efficiency were observed or calculated for furnaces, boilers, range top and oven burners, and water heaters (including standby losses).

I. Temperatures of Ignition System Components and Burners. All measured component temperatures were less than manufacturer specifications and no significant correlation was found between component temperatures and gas type.

5.3.2. Pulsed Combustion Burner (Jones and Leng 1996)

Jones and Leng (1996) measured the effect of varying fuel composition on CO and NO_X (NO and NO₂) emissions, air flow rate, and combustion chamber temperature for a commercially available non-premixed pulsed combustion room heater. They first varied the methane delivery rate then added varying amounts of H₂ or propane, first with the methane delivery rate fixed, then with the total fuel flow rate fixed. With just methane, a decrease in fuel flow rate led to a decrease in combustion chamber temperatures and a steady *increase* in excess air as the amplitude of the pressure pulse changed. Carbon monoxide emissions (expressed as CO/CO₂) reached a low point at moderate fuel flow, corresponding to about 60% excess air. At lower fuel flow rates, CO increased steadily. Nitrogen oxide increased steadily with fuel flow and measured temperature. At the lower fuel flow rates, the NO_X was mostly in the form of NO₂; at higher flow rates, it was mostly NO. This is explained conceptually as follows. Nitrogen oxide is formed as NO in areas where combustion occurs at near stoichiometric conditions. As mixing occurs, the temperature falls, moving towards the adiabatic flame temperature predicted from the overall air-fuel ratio. More NO is formed when the overall mixture is closer to stoichiometric because there is more time overall when combustion is happening at higher temperatures (that

is, it takes longer to cool down when there is less excess air). "The relative proportions of NO and NO2 are determined by subsequent mixing processes" including with the "backflow of combustion gases from the previous cycle." Increasing the flow of H2 at fixed methane flow (at the methane flow rate that corresponded to minimum CO) caused CO/CO₂ initially to decrease, then to increase. NO_X and NO had the inverse response to CO (increase then decrease with increasing H₂) but NO₂ had the same response as CO. These trends are again connected to the air flow rate, amount of excess air, and combustion temperatures. Initially, the drop in excess air causes temperatures to increase, NO production to increase, and CO to decrease. The latter may in part be related to the reduced importance of quenching as the walls of the combustor heat up. But as fuel flow increases, the amplitude of the pressure oscillation drops, and air flow rate drops. Past a certain point, the phase difference between the heat release and pressure oscillations approaches 90 degrees, Rayleigh's Criterion for self-sustained combustion is not satisfied, and the oscillations decrease to a point that results in incomplete combustion. A similar result is obtained when adding H2 at fixed total flow, though the magnitude of the changes in emissions is much less. Results for addition of propane are similar to those for pure methane. Interestingly, when propane is added at a fixed total fuel flow, there is little change in CO/CO₂ or NO₂ and variability in total NO_X (and NO) is much less than in the other cases. The relevance of this work to other types of burners and to variations in natural gas composition is unclear.

5.3.3. Effects on Emissions and Efficiency of Cookstove (Ko and Lin 2003)

This study examined the effects on pollutant emissions and thermal efficiency of a cooktop burner of varying five parameters: gas composition, primary aeration, gas flow rate (heat input), gas supply pressure, and loading height. The burner was designed for use with lower heating value NG. Efficiency was quantified as the amount of fuel energy required to heat 5 kg of water through a 50°C temperature rise (from 30°C to 80°C). Substitution of an NG with higher heating value (1102 Btu/scf) and Wobbe number (1414 Btu/scf) produced lower efficiency and higher CO emissions than a lower heating value (957 Btu/scf), lower Wobbe (1132 Btu/scf) fuel. Carbon monoxide emissions were reduced by decreasing gas supply pressure, by increasing the primary aeration, by selecting a proper thermal input, and by adjusting the height of the load. The load height is important as it affects the amount of flame impingement, a key element of CO formation.

5.3.4. Gas Technology Institute (Johnson and Rue 2003)

The objective of this study was to evaluate the interchangeability of potential LNG imports with typical domestic NGs on common residential appliances. The study additionally examined the ability of AGA and Weaver indices to predict impaired appliance performance with substitute gases and the relative effectiveness of diluting LNG with air or nitrogen.

Approach

Interchangeability tests were done on 11 new residential appliances and a test burner fashioned to replicate the early AGA work (AGA Laboratories 1946). The tested appliances included two tank water heaters, two ovens, two range-top burners, a clothes dryer, an unvented heater, a radiant heater, a forced air furnace, and an unvented fireplace. Appliances were installed and tested using adapted ANSI protocols. Interchangeability evaluation focused on flame stability, flame intensity, output temperatures, and exhaust CO levels during steady operation. The study

included one long-term test in which one new and one similar 11-year-old hot water heater were operated on a mixture of NG and propane to simulate an LNG while an identical WH used conventional (line) NG. This test was designed to examine long-term wear issues associated with using higher-heating-value gas. Water heaters were run for four months, during which the water in each was replaced six times per day.

Three representative domestic NGs (HHV = 1020-1042 Btu/scf; Wobbe = 1324-1336) were used as adjust (A) gases. Substitute (S) gases were six simulated LNGs based on samples from various producing regions, as shown in Table 4 below. All appliances and the test burner were operated with various gas blends using four mixing schemes. In mixing approach 1, a burner was tuned with 100% of the selected adjust gas then operated with increasing fractions of substitute gas. The test burner was run with substitute gases S1, S3, and S6—representing low, medium, and high heat content—each diluted with each adjust gas (nine combinations total). Appliances were tested with all 18 mixing combinations (6 substitute and 3 adjust gases). Mixing approaches 2 and 3 consisted of diluting substitute gases with N_2 or air to match heating value and Wobbe number of the adjust gases. Mixing approach 4 started with 100% of a substitute gas, to which increasing amounts of adjust gas were added. This is essentially the reverse of mixing approach 1 above. It is not entirely clear how the burner was tuned for this set of tests; but for appliances, the index values are calculated relative to A2 so it may be that the devices were tuned to this gas. In all cases above, tuning means setting air shutters to achieve a neutral flame (AGA flame code = 0).

Table 4. Simulated LNG test gases used in Johnson and Rue (2003)

Label	Country ¹	HHV (Btu/scf) ¹	Wobbe (Btu/scf) ¹
GTI Sub 1	Trinidad	1042	1373
GTI Sub 2	Algeria	1096	1399
GTI Sub 3	Qatar	1126	1417
GTI Sub 4	Abu Dhabi	1126	1417
GTI Sub 5	Malaysia	1156	1434
GTI Sub 6	Oman	1162	1437

¹ Properties based on sample(s) from each country of origin. Supplies coming from any single field will vary.

Interchangeability was evaluated by observations of flame stability and flame quality along with measurements of temperatures and exhaust gas concentrations. Flame quality was quantified using AGA flame code assessments determined by three experts who viewed digital photos of the flames. CO, CO₂, O₂, and NO_X were sampled in the exhaust stream using a probe that was moved to identify the point of highest or most consistent concentration for the non-

venting appliances. Temperature was measured at locations relevant to appliance operation (for example, inside the oven) and in places where changes in flame length could impact material surface temperatures (such as in the inlet manifold of the furnace). Flame intensity was quantified by analysis of brightness in individual pixels of digital images taken during testing.

Results

The test burner constructed by GTI satisfactorily replicated the original AGA results for lifting and flashback. When the test burner was tuned with an adjust gas then operated with increasing amounts of S1, S3, and S6, the flame code was close to 0 (ideal) for all but the largest variations. For example, when the burner was tuned to A1 and then operated on 100% S6, a flame code of -3 (nearing yellow tipping) was recorded. Much smaller flame variations were observed when the S gas was more similar to the A gas (for example, S1 and A3). When S gases were diluted with air or N_2 to have properties similar to the A gases, the largest flame variations were observed for S6 diluted to match the A gas heating values and when S3 was diluted to match the A gas Wobbe numbers. The worst cases of both test series produced flames that approached but did not cause actual lifting (AGA flame code = 3). The positive flame code values are expected since the inert components contribute momentum to gas mixture exiting the burner head but do not burn to increase the rate of heat transfer towards the port. Results were generally similar for the tests that started with 100% S gas and proceeded by diluted with A gas. In general, flame quality improved as the diluted LNG approached the properties of the A gas used to tune the burner.

Evaluation of gas interchangeability for appliances focused first on CO, a metric for which only one of the 11 devices (Oven 2) indicated a substantial effect. This finding is based on exponential type increases in CO with increasing fractions of substitute gas. As with the test burner, the highest CO was obtained from the combination of S6 with A1, the substitute and adjust gases having the most disparate properties. For most appliances, CO increased mildly (< 30%) or not at all with increasing amounts of S gas. Results for the fireplace, unvented heater, and Range 1 exhibited much more scatter in the data (± a factor 2 about the mean). Both water heaters and the dryer had consistent CO across all combinations of S and A gases. For the radiant heater, CO decreased slightly with increasing amounts of S gas. Following the completion of IX testing, it was found that removal of the bottom plate to gain access for flame viewing on Oven 1 had a substantial impact on CO formed by this device. It is thus unknown if CO emissions from this device would have been sensitive to gas quality changes.

The variations in CO for Oven 2 were used to investigate the predictive value of various IX indices, with a focus on those related to incomplete combustion. Both the Weaver and AGA yellow tipping indices (J_Y and I_Y) showed some value as cases of maximum CO increase were associated with the most extreme index values. However, even for this single appliance there was great variability in CO sensitivity for a given value of each index. Weaver indices for incomplete combustion (J_I) and the Wobbe ratio (J_H) also were sufficient to identify problem cases but had even more variability in CO sensitivity with a given index value. The ratio of heating value to specific gravity more cleanly identified the cases of highest CO sensitivity; it was therefore suggested that this parameter be further evaluated for its value as an IX index.

The effect of adding air or N_2 to reduce the heating value or Wobbe number of a substitute gas was demonstrated most convincingly with results for Oven 2, as this was the only appliance for

which CO increased substantially when operated with substitute gases. Increasing the amount of air or N_2 led to a decrease in exhaust CO levels for all substitute gases on Oven 2; CO levels dropped 40%–60% with up to 8% air or 6% N_2 .

The report notes some limitations in the approach used for quantifying flame intensity but concludes that it provides a reasonable measure of intensity for the radiant heater and a good measure of flame size for the other appliances. The flame intensity results were compared to various IX indices. The Weaver indices J_H and J_I correlated with the data, but it was concluded that I_Y was a better predictor of intensity ratio (flame size ratio). The intensity ratio increased substantially for the radiant heater (20%–70%) and fireplace (up to a factor of about 3); changes on the order of 10% or less were observed for the other appliances. Flame intensity was reduced when S gases were diluted with air; reductions of 20%–35% were obtained on the most sensitive devices (fireplace and Range 2). Dilution of S gases with air caused an increase in the flame intensity measurement for the radiant heater, a result that could not be explained.

Measured temperatures for most appliances were not substantially impacted by changes to fuel properties, for example, via mixing of adjust gas or air into substitute LNGs.

Over the four-month period of the long-term test, no clear trend of change was observed in the emissions or flue temperatures of any of the water heaters.

5.3.5. Southern California Gas Company / UC Riverside 2005

This study was performed in the context of expected changes to Southern California gas supply, including imports of LNG. Work was done under the auspices of the Southern California Gas Company (SCG) at several locations, including SCG's Engineering Analysis Center, the University of California at Riverside (UCR) Center for Environmental Research and Technology (CE-CERT), and several manufacturer locations. With a focus on residential and small commercial appliances, the stated objectives were the following: (1) evaluate safety and performance including carbon monoxide emission and flame stability, (2) compare measured results against interchangeability indices, and (3) collect NO_X emission data. A series of appendices document the protocols and results for each appliance tested. An overview of the study is provided in an executive summary (SCG 2005). At the time of this review, these materials are posted at the SCG website⁷ and are thus freely available for public review.

The basic construct of this study was similar to many others: appliances were adjusted with local line gas then operated with a collection of substitute gases using portions and adaptations of ANSI and other standard protocols. This study differentiates itself from previous work in a number of ways, starting with the quality, completeness, and availability of technical documentation. The study was well conceived and evaluates a suite of IX concerns, including the most extensive U.S. study to date of NO_X emissions impacts of gas quality changes.

Approach

Appliances were selected based on criteria targeting in-use and emerging devices and technologies known or thought to be sensitive to gas quality variability, and that exist or are expected to be employed in Southern California. These criteria were used to select the 13

⁷ www.socalgas.com/business/gasquality/researchstudy.shtml

appliances listed. Several of the tested appliances were being used by the general population prior to testing.

Test gases, shown in Table 5, included "baseline" SCG line gas and a series of substitute gases that spanned the limits of SCG's Tariff Rule 30 and included several intermediate gases. Following tuning and testing with Baseline gas, appliances were tested on at least two other gases: (1) the low heating value (HV), low Wobbe Gas 2, and (2) the high HV, high Wobbe Gas 3. If these tests indicated adverse gas quality sensitivity, additional tests were done with Gases 4–6 to determine if lowering the limits on heating value and/or Wobbe would produce acceptable performance. Selected appliances were further tested using Gases 4a and 5a that had similar properties but included more of the larger non-methane hydrocarbons; this was intended to assess the importance of gas composition independent of properties.

Appliances were tested with adaptations of standard protocols, including ANSI Z21 (operational safety) and South Coast Air Quality Management District (SCAQMD) protocols for NO_X emissions. Simplified device operating cycles were used in at lease some cases (for example, for the wall furnace). Emissions of CO and NO_X were measured during steady burner operation. Performance and safety evaluation included repeat ignition tests, overfire and underpressure operation, and specific tests for safety features such as an oxygen depletion sensor.

Table 5. Summary of experimental parameters in SCG (2005)

Appliances	Test Gases ¹	Effects Studied
Legacy water heater, used Legacy floor furnace, used Legacy wall furnace, used Condens. forced air furnace* FVIR water heater Instant water heater* Pool heater* Condens. boiler (comm.)* Hot water boiler (comm./ind.)* Steam boiler (comm./ind.)† Deep fat fryer, powered burner Char broiler, radiant, timed * low NO _X † ultra low NO _X	1. Baseline "average" SCG line gas: H=1020; W=1330 Test gas mixtures of C ₁ -C ₃ + N ₂ or CO ₂ : 2. H=970, W=1271 3. H=1150, W=1437 4. H=1150, W=1375 5. H=1100, W=1375 6. H=1100, W=1400 4a, 5a same as above with added C ₄ and C ₅	Flame stability; Emissions: CO, NO _X ; Ignition; Safety features; Performance Temps

¹ Test gas properties are heating value (H) and Wobbe number (W), in units of Btu/scf.

Results

The major findings of the study are presented on pages 20–22 of the report's executive summary (SCG 2005). These findings are summarized below:

- The study observed no performance issues associated with rapid switching of gases.
- All equipment operated safely and performed satisfactorily when set up with Baseline gas (H = 1020, W = 1330) then operated with Gas 2 (H = 970, W = 1271), Gas 4 (H = 1150, W = 1375), Gas 5 (H = 1100, W = 1375) or Gas 6 (H = 1100, W = 1400).
- Most equipment operated satisfactorily on Gas 3 (H = 1150, W = 1437), with these exceptions:
- CO emissions exceeded new appliance certification standards for the gravity wall furnace and the deep fat fryer.
- CO emissions increased significantly but did not exceed new appliance certification levels for the condensing boiler and pool heater tested on Gas 3.
- Operation with higher heating value/higher Wobbe gases produced higher exhaust temperatures for all units except the deep fat fryer.
- The chain-driven (time-based) charbroiler overcooked meat when using Gas 3 after being tuned to baseline gas, and undercooked meat when tuned to Gas 3 and operated on baseline gas.
- Neither heating value nor Wobbe number consistently correlated with performance.
- Analysis with standard interchangeability indices predicted potential problems with three of the gas blends, yet problematic performance was encountered with only two appliances on one blend (Gas 3).
- NO_X emissions were, in general, positively correlated with heating value and Wobbe number.
- Four of five low- NO_X burners had very sharp increases in NO_X when operated with the higher heating value/higher Wobbe number gases.
- Several units exhibited NO_X sensitivity related specifically to a greater number of hydrocarbon species (for a fixed heating value or Wobbe number).
- The ultra-low-NO_X boiler—which represented the newest technology device—showed little NO_X sensitivity to heating value/Wobbe number.
- The indoor residential appliances did not exhibit significant NO_X sensitivity to gas composition.
- "As received" fuel input rates for several new, residential devices were < 90% of ratings.
- CO emissions of the instantaneous water heater were extremely sensitive to gas supply pulsations caused by an upstream regulator.

Additional results from this study are discussed later in the context of specific IX concerns.

5.3.6. Advantica Pilot Study (DTI, U.K.) (Williams et al. 2004)

This is the first of three reports on experimental work examining gas interchangeability on U.K. appliances. The study aimed to investigate the following possible effects of a gas quality change: (1) operability including ignition and flame stability, (2) device surface temperatures, (3) pollutant emissions (CO₂, CO, NO/NO₂/NO_X, soot), and (4) thermal efficiency. The results of this study were used in the design of the follow-up studies described below.

Approach

In this pilot phase of the work, five appliances were tested on a wide range of gas mixtures. Units typical of the four most common U.K. residential gas appliances were selected; these included a gas fire with decorative flame effect; a freestanding cooker (analogous to a "range" in the United States) with four hotplate burners, a grill burner, and an oven burner; an instantaneous natural draft water heater; and a fan-assisted boiler. These four devices were intended to represent older in-use appliances manufactured prior to standards that took effect in 1995 (Gas Appliance Directive 90/396/EEC). The fifth test appliance was a modern condensing boiler with premix burner. Three sets of test gases were used. The first set of gases contained methane mixed with propane or nitrogen to achieve Wobbe numbers ranging from 46 to 55 MJ m⁻³ (~1235–1475 Btu/scf), at 1 MJ m⁻³ increments; these tests were intended to test the effect of Wobbe number. The second and third sets of gases were intended to test the effects of relatively high (6% by volume) N₂ or CO₂; these consisted of N₂ or CO₂ mixed with methane and propane to achieve Wobbe numbers of 46, 48, 51, 52, and 55 MJ m⁻³. Baseline data were obtained by testing the devices as received with 100% methane, which is the G20 reference adjust gas (100% methane, 50.7 MJ m⁻³ ≈ 1360 Btu/scf) used in the U.K. In accordance with standard test procedures, pollutant emissions were measured during stabilized burner operation. Protocols were adapted by using shorter cool-down times between tests based on the rationale that the measurement conditions were for hot stabilized operation. Burners were tested at low, medium, and high input rates, as feasible. A series of cold-start tests were conducted with selected gases. Additional tests were conducted to confirm the theoretical relationship between Wobbe number and heat input.

Results

The publicly available report includes extensive results; the major findings associated with the objectives identified above are summarized below.

Operability: No short-term operability problems were encountered: ignition occurred for all test gases, and flames were generally stable. For the standard boiler, flames appeared "overgassed" (longer, yellow flames) with higher Wobbe number gases. Longer yellow flames were observed also for the gas fire and cooker flame with higher Wobbe gases. The highest Wobbe gases produced flames that hung down almost to the pan below the grill burner. These longer flames were associated with increased CO and soot production for the standard boiler, increased soot without increased CO for the fire, and no major increase in pollutants from the cooker flame. Soot production, which occurred for two of the appliances, could present longer-term operability concerns, including deposition on heat exchangers, reduced heat input, lower efficiency, and potentially blockage of injectors or narrow finned heat exchangers.

Casing Temperatures: External surface temperatures did not exceed limits in relevant test standards. Only for the standard boiler did the temperature of the case increase with Wobbe number.

Pollutant Emissions: Increasing the Wobbe number of the test gas produced substantially higher emissions of some pollutants for some of the appliances. At the highest fuel delivery rate, CO and CO/CO₂ increased sharply with Wobbe above 52 MJ m⁻³ (~1400 Btu/scf) for the condensing boiler and standard boiler. CO values for the standard boiler were above the U.K. standard of 1000 ppm on a daf basis for the highest Wobbe gas, and CO/CO₂ was above the standard of 0.008 for Wobbe ≥ 54 MJ m⁻³ (1450 Btu/scf). For the condensing boiler, CO was < 200 ppm daf at Wobbe ≥ 53 MJ m⁻³ (1420 Btu/scf). CO and CO/CO₂ increased with Wobbe for the cooker; max values were 500-1000 ppm daf at Wobbe \geq 53 MJ m⁻³ (1420 Btu/scf). For the fire, CO varied widely, with no clear trend by Wobbe. Exhaust concentrations of NO_X increased sharply for Wobbe ≥ 53 MJ m⁻³ for the condensing boiler. NO_X increased gradually (linearly with some noise) across the entire Wobbe range for standard boiler and on-demand water heater; the increase was > 100% for NO_X. The cooker was not sensitive to NO_X. The gas fire and standard boiler produced significant amounts of soot. The standard boiler produced soot only at Wobbe of 53 to 56 MJ m⁻³ (1420–1490 Btu/scf) with no dependence on diluent used. The gas fire produced soot across entire Wobbe range, but soot increased at higher Wobbe. For the fire, gases diluted with N2 had higher soot than gases with CO2 or methane-propane mixtures having the same Wobbe number.

Efficiency and Flue Gas Temperature: Both thermal efficiency and flue gas temperature were marginally sensitive to the Wobbe number of the gas. Efficiency changes were not discernible for the cooker and fire, and rose minimally (0.25% to 2.5%) for the other appliances as Wobbe number was increased.

Addition of CO_2 or N_2 : Dilution with CO_2 or N_2 to reduce Wobbe number brought emissions down to similar levels as base gases having the same Wobbe values.

5.3.7. Advantica (DTI, U.K.) (Williams et al. 2005)

Advantica tested 10 additional appliances as follow-up to the pilot study described above. The objectives and methods of this follow-up study were similar to the pilot phase, except that gases were diluted with N_2 only. This phase of the study also included a longer operation test for a gas fire.

Approach

Ten used appliances (aged 1–10 years) were procured from homes or training programs; all were manufactured to meet the standard of the 1995 Gas Appliance Directive. The following devices were tested:

- Boiler: open-flued, floor standing (older style).
- Cooker (range): free standing with eye-level grill.
- Back boiler unit (BBU): includes live fuel effect flame in front for room heat.
- Condensing boiler 1: wall-mounted, fanned flue.
- Live fuel effect fire (LFE): open-fronted.

- Air heater (furnace): open-flued.
- Water heater: flueless, single point (tankless).
- Condensing combination boiler: wall-mounted, fanned flue combines instant hot water with heating water for radiant system.
- Condensing boiler 2: wall-mounted, fanned flue.
- Flueless fire: LFE with catalyst, glass-fronted.

Appliances were tested on three series of gases. The first comprised mixtures of methane plus nitrogen or propane to achieve Wobbe numbers ranging from 45–56 MJ m⁻³ (1210–1500 Btu/scf). Also tested were mixtures of the higher Wobbe methane/propane gases diluted with enough N₂ to achieve Wobbe numbers similar to the G20 reference adjust gas), and gases with a fixed 6% N₂ content at Wobbe numbers of 52–54 MJ m⁻³. As in the pilot phase, standard methods were used to study ignition, efficiency, and pollutant emissions. Devices were tested on the varied gas mixtures as-received and again after servicing and adjustment with G20/methane.

Results

The publicly available report includes extensive results; the major findings are summarized below. Additional results are provided in the discussion of interchangeability concerns.

Operability: No major operational problems were reported as appliances were operated on the varied test gases. Ignition occurred and flames were stable in all cases.

Casting Temperatures: Only one device (the flueless fire) had elevated temperatures on a surface accessible to users, but this occurred for most gases, including the G20 (methane) reference gas.

Pollutant Emissions: There was a general trend of increasing CO emissions with increasing Wobbe number for most appliances. On many appliances, CO increased much more sharply at WNs ≥ 51 MJ m⁻³ (~1370 Btu/scf). Some appliances having high baseline CO emissions as received (that is, the cooker hob and live fuel effect fire) did not exhibit CO sensitivity to gas quality variability; that is, emissions did not discernibly increase with the Wobbe number of the test gas. NO_X emissions generally increased with increasing Wobbe number of the test gas. Absolute levels were lower but increased more sharply with Wobbe number for appliances with full premix burners. Direct soot emissions were not observed for many appliances and gases, but soot production occurred at Wobbe numbers ≥ 53 MJ m⁻³ for some appliances (notably gas fires). The effect of Wobbe number on direct NO₂ emissions varied by appliance, but the changes in direct NO₂ generally were much smaller on a relative basis than the effect on total NO_X.

Efficiency: Gas quality variability produced small or indiscernible changes to measured efficiency in all appliances.

Nitrogen Ballasting: Addition of nitrogen to higher WN gases generally led to a reduction in pollutant emissions to levels observed with base gases having the same WN as the final nitrogen-ballasted gas. Gases containing a fixed 6% N₂ generally produced results identical to other gases having the same WN. Nitrogen (N₂) addition does not appear to have any direct effect on NO_X; the effect of N₂ is primarily via its impact on WN and combustion stoichiometry.

Long-Term Test: The live fuel effect fire was operated with a 6-hour-on, 2-hour-off cycle over 12.5 days with a 54 MJ m⁻³ methane-propane gas. Emissions of CO and NO_X did not change substantially over this period, but soot deposition was observed on several coals and in the base beneath the burner assembly.

5.3.8. BSRIA (DTI, U.K.) (Teekaram et al. 2005)

This study was conducted in parallel to the 2005 Advantica study, as follow-up to the 2004 Advantica pilot study described above. It used the same experimental methods and test gases as the 2005 Advantica study and sought to answer the same questions. The 10 appliances tested included 5 boilers, 2 cookers, an instant water heater, a decorative fuel effect fire, and a radiant ceramic fire. The boilers included one combination unit with room sealed balanced flue, one condensing unit with premix burner, two standard units (one with open flue), and a back boiler unit. The majority of the test appliances were removed from dwellings. As with the other DTIsponsored studies, the results of this work are readily available to the public via the DTI website (www.dti.gov.uk/energy/markets/gas-quality/phase-2/page21044.html). Results of this study were consistent with those described above. There were no major operability problems. Emissions of CO and NO_X generally increased with the Wobbe number of the test gas. For some devices, CO increased sharply for gases having Wobbe numbers > 51 MJ m⁻³. NO_X increased more sharply with Wobbe number for the newer premix burners relative to the conventional partial premix burners. A long-term test was conducted with a lean premix, high-efficiency boiler, which was operated for 30 minutes on, 10 minutes off for a total of 240 hours. Over this time there was no change in NO_X emissions or efficiency, CO emissions increased by about 20%, and no soot was observed.

5.4. Pollutant Emissions from Natural Gas Appliances

Individual studies of pollutant emissions associated with residential natural gas appliances are not reviewed in detail, as this report focuses on the impact of gas quality changes on performance and emissions.

5.5. Prediction of Interchangeability from Combustion Fundamentals

Appliance-related gas interchangeability concerns can be examined through analysis of fundamental combustion parameters. In fact, Levinsky has argued that this predictive capability has been developed and validated to the point that further experimentation is no longer required for some IX concerns (Levinsky 2006). A 2004 conference paper (Levinsky 2004) uses this approach to examine the impact of "new" gas formulation (including LNG) on emissions of CO and NO_X and on flame stability. The paper states that there are two possible causes for increased CO emissions associated with gas quality changes⁸: (1) an increase in equilibrium CO concentration just beyond the primary flame front, and (2) supplemental CO production associated with partial lifting. In the latter case, fuel escaping as the flame lifts at the burner edge is partially oxidized to CO in the upper region of the flames of adjacent burner ports (Van der Meij et al. 1994). The second path is regarded as less relevant to analysis of LNG

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⁸ This analysis does not consider the role of flame impingement on CO emissions. Thus, to the extent that a change in gas quality alters the likelihood or characteristics of impingement, this analysis may not predict the full effect of gas quality on CO emissions.

effects (presumably since the higher Wobbe LNG blends are not expected to cause such partial lifting). For the partial-premix flames common to gas appliances, an increase in the fuel Wobbe number shifts the primary fuel air ratio to produce a richer flame front with higher equilibrium CO concentrations. Composition has a secondary but discernible effect on CO. The effect of gas quality on CO emissions for an appliance population can thus be evaluated by calculation of the equilibrium CO just past the primary flame front. An acceptable limit of variability can be set by historical variability or by an acceptable CO increase. NO_X production is discussed in the context of lean premix burners. An increase in the Wobbe index will shift the primary air-fuel mixture in the direction of stoichiometric combustion, resulting in much higher flame temperature and large increases in thermal NO_X production. The conference paper concludes with a discussion of laminar burning velocity as the key parameter for assessing the potential for flashback when hydrogen is added to natural gas.

In a report to the U.K. DTI, Levinsky (2005) presents an analysis of the soot production potential of gas mixtures that is based fundamentally on the soot-forming potential of the component NMHC. Here soot-forming potential is calculated using experimentally measured critical equivalence ratios of the individual NMHC (Takahashi 1997). The Gasunie Soot Index (GSI) relates the soot-forming potential of any substitute gas to that of a selected limit gas on a theoretical appliance that is adjusted to just-barely not produce soot with the limit gas.⁹ In other words, the theoretical appliance provides just enough primary air for the equivalence ratio in the primary flame front to be just below the critical value. When another (substitute) gas of different composition is used, both the primary equivalence ratio and the critical equivalence ratio for soot formation can change. Changes to the relative proportions of NMHC, especially those associated with diluting higher Wobbe gases with inert components (such as N2) can cause the actual and critical equivalence ratios to shift in different proportions. Thus the Wobbe index alone does not provide a sufficiently specific limit for soot formation. The GSI is compared to the SI and ICF metrics developed by Dutton based on actual appliance testing. While the SI correlates well to the GSI, the ICF (with an upper limit of 0.48) gives almost identical predictions of acceptability for most gas mixtures examined.

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⁹ Soot formation is considered here in the context of an isolated premix flame, with the primary equivalence ratio as the key variable. In real devices, flame impingement can additionally impact soot emissions. Thus, as in the note above, the analysis may not capture the entirety of gas quality effects on soot formation in real appliances.

6.0 Summary of Common Conclusions

The evaluation of NG interchangeability, specifically as it relates to the incorporation of LNG and potential mitigations, can be framed by the following set of questions.

- What are the factors that affect interchangeability for residential appliances?
- Based on previous studies of gas interchangeability for appliances, which effects have been found to be significant and which have been found to be of minimal or no concern?
- Are there specific appliances and burner technologies that are especially sensitive to gas quality changes?
- Are there factors specifically associated with in-use appliances which are important to interchangeability?
- Are there specific operating modes that are especially sensitive with respect to interchangeability?
- Can high Wobbe gases be diluted with nitrogen, carbon dioxide, or air to achieve acceptable performance? Are the three diluents equivalent?
- Can IX effects be predicted using existing indices? Are the limits used historically still relevant or do they need to be modified?

6.1. Factors that Affect Interchangeability for Residential Appliances

The following factors may impact whether a given device will experience any adverse performance or emission impacts as a result of supply gas quality changes:

- 1. Device technology and design characteristics. Included in this category are burner type, combustion chamber design, primary aeration, amount of excess air, and any other physical features that may affect combustion or be affected by changes in flame temperature, flame length, or other flame properties. Refer to Appendix A for additional information about appliance and component technologies.
- 2. Device operational condition. This category includes factors related to device set-up (2a and 2b), maintenance (2b–2d), device and component quality (2d), and other factors related to device installation (2e), as listed below:
 - 2a. Properties of the natural gas used for last rating and adjustment.
 - 2b. Quality of device installation, rating, and adjustment.
 - 2c. Possible tampering or other "adjustments" made following last rating/adjustment.
 - 2d. Age/wear of device and state of repair of device components.
 - 2e. Other factors including gas supply pressure and stability.
- 3. *Properties and composition of substitute gas.* The rate of gas switching is a potentially important factor, but previous studies have not found this to be the case.
- 4. *Device use patterns*. Device operational patterns may vary among users, including more or less steady-state or intermittent operation, routine or extreme application, and other factors.

5. *Environmental conditions*. Important parameters include air temperature, humidity, and pressure (which is primarily dependent on elevation).

6.2. IX Effects Observed for Residential Appliances

Many past studies examined pairs or collections of gas mixtures that varied in composition and Wobbe number much more broadly than the variations that are expected for distributed gas in California. For example Griffiths et al. (1982) examined pairs of adjust and substitute gases that had Wobbe ratios of 1.1–1.2. The studies conducted by ACLC, AGA, and AGC in support of Elba Island in the 1970s (TIAX 2004a) examined performance of devices adjusted to then-current NGs having Wobbe numbers of 1340–1355 Btu/scf, then operated on an Algerian LNG blend with Wobbe number of about 1455 Btu/scf (ratio of about 1.07). The SCG (2005) study included test gases with Wobbe numbers that were 8% higher and 4% lower than that of the adjust gas at 1330 Btu/scf. The DTI-sponsored studies in the U.K. examined an even wider range of gases. By contrast, the Wobbe limit recently approved by the CPUC (1385 Btu/scf) is only about 4% higher than systemwide typical value of 1330 Btu/scf for Southern California (SCG 2005).

Past studies have also examined devices having a wide range of initial adjustments, and in many cases the adjustments were designed to test the appliance in the most sensitive mode that could be envisioned.

In this summary review of observed effects, the focus is on those that appear to be relevant to the relatively small increase in gas variability that will occur in California in the near term (based on the recent CPUC decision) or that might become relevant if the gas quality limits are expanded.

6.2.1. Ignition

There is no indication based on existing information that ignition problems will result from expected changes to gas quality. Many studies have examined ignition either ad-hoc or systematically. For example, ignition tests were performed on most appliances in the SCG (2005) study using the highest and lowest Wobbe number gases (2 and 3) in addition to baseline gas, and in some cases the test was repeated for under- and over-fired conditions or for hot and cold starts. No ignition problems were observed for the residential appliances. Ignition was similarly not found to be affected by gas quality changes in the other major studies reviewed (Johnson and Rue 2003; TIAX 2004a; Williams et al. 2004; Williams et al. 2005).

6.2.2. Flame Stability

Flashback is a concern primarily when switching from a slow-burning fuel like natural gas to a faster burning fuel like hydrogen; it is a non-issue when switching among natural gases and LNGs, based on both theoretical considerations and extensive empirical evidence in the many studies reviewed for this report.

Lifting is of potential concern when switching from a higher Wobbe gas to a lower Wobbe gas. When appliances are set to provide enough air to combust a higher Wobbe fuel, a decrease in Wobbe (for example, by inclusion of more inert components) translates to a reduction in energy flux (heat transfer) at the flame front. Since the energy flux of the fuel and air exiting the burner does not change, the flame front will move away from the burner.

Lifting has been an effect of interest in many IX studies yet there are almost no reports of lifting occurring with appliances operating in a steady (warmed) mode. This is true even for large changes (reductions) in Wobbe number from adjust to substitute gas (Griffiths et al. 1982). The TIAX (2004a) Elba Island report cites the AGA 1974 study, in which partial lifting occurred with burners that were cold, then resolved as the burners warmed.

6.2.3. Flame codes

The AGA flame code scale establishes a standard range of acceptable flame appearance and provides a means to describe deviations from acceptability. Flame codes were used explicitly as an outcome metric in Johnson and Rue (2003) but are not reported in other studies.

6.2.4. Flame Lengthening

Several studies have reported flame lengthening when appliances were operated with higher Wobbe substitute gases including LNG blends; examples include the AGC 1978 study (TIAX 2004a) and the GTI 2003 study (Johnson and Rue 2003). BG&E observed that range pilot flame lengthening was a somewhat widespread problem in the field when LNG was distributed in 1978 (Steinmetz 1979).

Flame lengthening with increasing Wobbe number was also reported for several appliances in the Advantica 2004 Pilot Study (Williams et al. 2004). For the standard boiler, flames appeared "overgassed," and this condition was associated with higher emissions of CO and soot (exceeding "normal" operation limits for CO and acceptable limits for soot). The gas fire also had longer, more yellow flames at higher Wobbe with associated soot production; however CO did not increase with Wobbe number for this appliance. Moderate effects were observed on the cooker, with shorter blue flames for the mixtures containing CO₂ and longer, lazy flames for the highest propane content gases. On the grill burner, the highest Wobbe gases produced flames that hung down and almost touched the grill pan.

Flame lengthening can lead to impingement with potentially important implications for emissions of CO, soot, and other products of incomplete combustion.

6.2.5. Flame Temperature

The importance of flame temperature can be assessed from a simplified theoretical perspective if combustion stoichiometry is known or assumed (Kuipers 2005). However, in the partially premixed flames normally found in appliances, it is extremely difficult to predict pollutant formation rates from theoretical considerations, since the temperature is only one of the controlling parameters. The complete temperature field and fluid mechanics are needed, and the calculations are complex and costly. It is also difficult to directly and accurately measure the flame temperatures in these systems, and none of the experimental studies that were reviewed reported direct measurements of flame temperature. Flame temperature nevertheless has value as a relative indicator of NO_X formation potential, as elucidated by Levinsky (2004).

6.2.6. Pilot Light Stability

A number of issues related to pilot burners have been reported, but stability is not among them.

6.2.7. Safety Feature Performance

The potential for gas quality variations to effect safety feature performance is a relatively new concern, in part because several key safety features are relatively new additions to appliance designs. There are two interchangeability concerns related to safety feature operation. The first is that the gas quality change could directly impair performance of the safety device, for example, by changing the flame characteristics. The second is that the gas quality change could lead to a sharp increase in pollutant emissions that could increase the chances that the safety feature would be needed.

As part of their study for SLNG in 2001, TIAX tested the performance of the oxygen depletion sensor (ODS) on an unvented infrared heater operated with unblended Australian LNG. The device was operated with the pilot only in a hood that was filled with air from another furnace. The ODS operated within the ANSI requirement and shut off the appliance when O₂ decreased to about 18%.

Advantica (2005) tested three devices: a flame sensor (FSD), a temperature sensor (TTB), and an oxygen depletion sensor. The FSD and TTB devices exhibited minor variations in performance associated with gas quality variability, but all tested units operated within standards. ODS units on several devices did not operate as required. The report states that "the Wobbe Number of the test gas can have a significant impact" on ODS operation. However, for at least two devices (live fuel effect fire and back boiler unit), ODS failures were not clearly associated with gas quality changes based on the results shown. For the other two devices, it is unclear if the ODS was directly affected by gas quality or if it was just that the metrics used to gauge performance (CO and CO_2 levels) were affected by the gas quality change.

6.2.8. Performance Temperatures

In some devices, use of higher Wobbe gas increases temperatures of device components, exhaust gases, and/or the fluid being heated (air or water) by the appliance; likewise, dilution of the higher Wobbe LNG with inert components can lower the observed temperatures. However the measured temperature changes generally have been small, and the effect of these variations on device performance is unclear (Johnson and Rue 2003).

6.2.9. Accelerated Equipment Wear

This impact is challenging to assess based on short-term tests. The Advantica study (Williams et al. 2005) notes explicitly that there was no indication of excessive stress or overheating that would accelerate material failure.

6.2.10. Touchable Surface Temperatures

In the Advantica 2004 study (Williams et al. 2004), surface temperature on the front of the standard boiler increased with increasing Wobbe number, but values never exceeded limits of the applicable test standard (EN 483). Surface temperatures were low and/or independent of Wobbe for the other appliances. In the Advantica 2005 study (Williams et al. 2005), touchable surface temperatures were above allowable limits for only one appliance—a flueless fire—but this occurred for most gases including the G20 adjust gas, which is 100% methane.

6.2.11. Specific Performance Issues

The SCG (2005) study demonstrated that a chain-driven char-broiler is at least one device that has a specific performance issue linked to gas quality. Once the speed of the chain is set to provide an appropriate cooking time with the adjust gas, any significant change to the Wobbe number of the supply gas will affect cooking. A switch to a lower Wobbe gas will result in undercooking, whereas a higher Wobbe gas will cause overcooking. There may be other devices and applications that fall into this category.

6.2.12. Thermal or Energy Efficiency

Exchanging one natural gas for another with a modestly different Wobbe number is expected to cause very small changes in efficiency for most appliances, as discussed in TIAX (2004a). Experimental results reported by Griffiths et al. (1982) and the DTI (U.K.) studies provide extensive empirical support for this. As an example, the standard boiler tested by Advantica (Williams et al. 2004) exhibited an efficiency increase from 92.3% to 93.1% across the wide Wobbe range of test gases. The condensing boiler efficiency varied from 97.25% to 97.5% across the Wobbe range of test gases. The instantaneous water heater efficiency increased from 87.5% to 90% across the range of gases. Sensitivity of efficiency to Wobbe number of N₂- and CO₂-diluted gases was similar for all three of these appliances. For the cooker and fire, efficiency was completely insensitive to the Wobbe number of the test gases. The follow-up study by Advantica (Williams et al. 2005) reported a "flat" efficiency response as a function of Wobbe number, except for two appliances: the cooker hob and the water heater. For the cooker hob, efficiency increased with Wobbe number up to G20 (50.7 MJ m⁻³), then declined slightly. The water heater had flat response across most test gases, then efficiency decreased with the highest Wobbe gases (55–56 MJ m⁻³).

6.2.13. Incomplete Combustion

The potential of fuel changes or gas quality variability to cause or increase levels of incomplete combustion was examined explicitly as one of the IX indices of Weaver; since then, many studies have revisited this endpoint of concern. Because incomplete combustion is evaluated through measurements of exhaust CO concentrations or the CO/CO₂ concentration ratio, the research team did not separately review studies that nominally named incomplete combustion as an endpoint of interest. The effect of fuel changes on CO emissions are addressed below, with a focus on studies of the most relevance to the current appliance population.

6.2.14. Carbon Monoxide (CO)

Potential changes to CO emissions have been a major focus of almost all interchangeability studies to date, and many have observed some level of CO sensitivity to gas quality. These results therefore are reviewed in some depth.

The theoretical effect of raising natural gas Wobbe number on CO emissions has been explained by Levinsky (2004) as summarized above. With a higher Wobbe gas, more chemical energy is introduced with a fixed primary air supply; the result for a partial premix burner is a primary flame that is more fuel rich and thus has higher equilibrium CO just past the flame front. The additional CO formed will typically burn to completion (that is, to CO₂) in the secondary flame but could in some cases result in a net increase in CO exhaust emissions. However, this considers only the CO production that is associated with the primary air-fuel ratio and

associated equilibrium CO concentrations. Carbon monoxide emissions can also result from quenching or interruption of the flame on surfaces, a process that can be affected by the flame height and physical characteristics. Thus, it is important to consider the experimental results in addition to the theoretical predictions.

Carbon monoxide sensitivity was a key effect examined in four IX studies conducted in the early 1970s in connection to the start of operations for the Elba Island and Cove Point receiving terminals (TIAX, 2004a). Appliances were adjusted with domestic NG and operated with Algerian LNG (Wobbe ratio of approximately 1.08). Carbon monoxide was considered "acceptable" for most of the tests, with the following exceptions. One furnace (of 18 appliances) tested by the AGA in 1974 had CO sensitivity to the Algerian LNG, and this sensitivity was more pronounced when the primary air was adjusted to give a soft flame with NG. The AGLC 1975 study (see TIAX 2004a) found high CO for one water heater with a "Saturn" burner at overfire conditions and high CO for 8 of 20 radiant heaters tested on *both* NG and LNG. It was not noted if CO was higher for LNG than NG; thus, it is not clear if these appliances have a special sensitivity to gas changes or simply are prone to high CO.

The GRI-sponsored 1982 study (Griffiths et al. 1982) examined pairs of adjust and substitute gases that differed much more than what is generally being considered for interchangeability in the United States, and specifically in California for the foreseeable future. For example, when appliances were rated for the lifting limit gas L and operated with the yellow tipping limit gas Y (Wobbe index = 1432/1179 = 1.21), many appliances had exhaust CO concentrations more than 800 ppm (10 of 17 tested with maximum or fixed primary air). Substitution of baseline adjust gas A in burners rated for L (Wobbe index = 1296/1179 = 1.10) produced CO above 800 ppm in 2 of 16 appliances tested with maximum or fixed primary air supply. Two additional appliances had CO emissions increase by more than a factor of 3 relative to operation on the adjust gas. Similarly, substitution of yellow tipping gas Y in burners rated for the A gas (Wobbe index = 1432/1296 = 1.10) produced exhaust CO above 800 ppm in 5 of 17 appliances tested with maximum or fixed air supply and led to substantial increases relative to adjust gas A in 2 additional appliances. When adjusted with the A gas and with primary aeration set to a "reasonable" level, 19 of the 31 appliances had acceptable CO emissions on all test gases. Four of the appliances had CO levels exceed limits specified by appropriate ANSI test standards (three with Y gas, one with all gases).

The GTI 2003 study (Johnson and Rue 2003) reported CO concerns for only one of 11 new appliances tested (Oven 2). This was a tube-type burner with a plate on top. Exhaust CO increased approximately exponentially with Wobbe number as the six substitute (Sub) gases were used after the device was tuned to the Adjust 1 gas (see the figure on p. 106 of GTI report). Researchers observed a relatively continuous trend with the pure substitute gases, which varied in Wobbe number, and as the pure substitute gases were diluted with adjust gas, leading to intermediate Wobbe number mixtures (see Figure 5.12 of GTI report). Absolute concentrations for the highest Wobbe gases were approximately 1.5–3.5 times those measured for the Adjust 1 gas, but the highest levels measured were still below or near the ANSI limit of 400 ppm on a dry air-free basis. Carbon monoxide also increased when the substitute gases were used following tuning to the other two adjust gases, but the increases were much smaller. Carbon monoxide emissions from Oven 1 were impacted by removal of the bottom plate to gain access to view the flame. It was noted that CO was higher when the plate was in place, but this standard

configuration was not studied with varied gases. The other appliances generally did not exhibit CO increases across the various combinations of adjust and substitute gases. However, CO results for three of the appliances (Fireplace, Unvented heater, and Range 1) cannot be considered as definitive because large test-to-test variations were observed. The authors attribute this to measurement uncertainty associated with direct sampling of exhaust streams with large amounts of excess air (leading to very low CO, and O₂ concentrations that are close to background air).

In the SCG 2005 study, large CO increases were observed on 4 of 13 appliances with the highest heating value and highest Wobbe substitute gas (Gas 3: H = 1150 Btu/scf, W = 1437 Btu/scf). Exhaust CO increased by 1200 ppm for the deep fat fryer, by 180 ppm for the legacy wall furnace, by 120–160 ppm for the condensing boiler and by 70 ppm for the pool heater. However, absolute levels of exhaust CO with Gas 3 were only 185, 200–265, and 95 ppm, respectively, for the wall furnace, condensing boiler, and pool heater. The wall furnace, pool heater, and deep fat fryer showed almost no CO increases for other test gases, including test Gas 6 with a Wobbe of 1400. Exhaust CO was not substantially affected by fuel changes for other appliances, with one exception. Carbon monoxide emissions of the instantaneous water heater were extremely sensitive to gas supply pulsations caused by an upstream regulator; with the unstable regulator, emissions increased from about 300 ppm with the baseline gas to about 1200 ppm with Gas 3 under steady operation.

The TIAX Cove Point study (TIAX 2003) reports CO "sensitivity" for 13 of 24 appliances but does not explain what this means quantitatively.

The three DTI-sponsored studies (Teekaram et al. 2005; Williams et al. 2004; Williams et al. 2005) report CO results for 25 U.K. appliances, several of which contained multiple burners or components (such as combination boilers and gas fires). Most of the appliances were in-use in residences prior to testing. The burners were operated on two or three component (methane plus propane and/or nitrogen) gases spanning a wide range of Wobbe numbers. Test gases spanned a Wobbe range of –11% to +10% relative to the U.K. G20 adjust gas (methane). The following trends were observed when testing appliances as received:

- 1. Almost all of the boilers with standard burners had CO increase with Wobbe number in an apparently exponential or bilinear fashion. Three of four boilers with premix burners also had CO increase with Wobbe number in an exponential or bilinear fashion. A similar pattern was observed for a warm air heater (furnace) and one of the three instant hot water heaters. The inflection point for almost all of these appliances was at or near the Wobbe number of the adjust gas.
- 2. For several other appliances, CO did not increase substantially with Wobbe number of the test gas. These included all five of the decorative effect gas fires, three of the four cooktop burners, three of the four ovens, two of the three cooker grills, and one of the three instant water heaters.
- 3. CO sensitivities were observed for units that had a wide range of absolute CO emission levels. Several appliances had large relative increases in CO emission level, but even at the highest Wobbe gases, absolute CO levels were still well below the U.K. regulatory limit of 0.1% on a dry, air-free basis.

- 4. On four of the boilers, sharp CO increases produced levels above the U.K. standard of 0.1% when operated on the highest Wobbe gases; these included the Standard Boiler in (Williams et al. 2004), the Condensing Boiler 1 (before service) in Williams et al. (2005), and the Standard Boiler 4 (after service but not before) and Back Boiler 5 (before and after service) in Teekaram et al. (2005). This result suggests that CO sensitivity to gas quality changes cannot always be fixed by routine service.
- 5. Several appliances had exhaust CO concentrations above the standard on some gases but did not show a clear sensitivity to higher Wobbe gases. These included the cooker hob (after service) and the "live fuel effect" fire both before and after service in Williams et al. (2005) and the "decorative fuel effect" fire before and after service in Teekaram et al. (2005).

6.2.15. Nitrogen Oxides (NO_x)

The only studies to date to report experimental results for NO_X are SCG (2005) and the DTI-sponsored studies (Teekaram et al. 2005; Williams et al. 2004; Williams et al. 2005).

The SCG 2005 study reports extensive results for NO_X . Summary findings described below are based on those listed in the summary final report and on review of the appendix data tables. The test gases used in this study had target¹⁰ Wobbe numbers ranging from 1271 to 1437 Btu/scf, corresponding to Wobbe ratios of 0.96 to 1.08 (-4 to +8%), relative to the adjust gas.

- 1. For four of the five appliances with "low NO_X " burners, NO_X increased sharply and approximately linearly with Wobbe number. Approximate increases from lowest to highest Wobbe gases were as follows: residential pool heater, $4\times$; commercial condensing hot water boiler, $2.5\times$; commercial-industrial hot water boiler, $4\times$; and commercial-industrial steam boiler, $3.5\times$. All of these used full premix burners. NO_X did not increase with Wobbe number for the condensing forced-air furnace, which uses an induced combustion "low NO_X " burner system with in-shot burners.
- 2. For legacy appliances with atmospheric burners, NO_X emissions did not increase consistently with the heating value or Wobbe number of the test gas. These appliances included the storage water heater, floor furnace, gravity wall furnace, and the flammable vapor ignition resistant water heater (atmospheric burner with limited air).
- 3. For the ultra-low- NO_X steam boiler, NO_X increased linearly with Wobbe number by about 60% over the range of gases. For the deep fat fryer NO_X increased by about a factor of 2 over the range of gases. Absolute NO_X levels for these devices were much lower than for the other appliances tested.
- 4. For the chain-driven charbroiler and instantaneous water heater, NO_X appeared to increase with Wobbe number of the test gas, but with large uncertainty. Estimated increases were about 1.5 and 1.3 times for the broiler and instant water heater, respectively, over the range of gases.

¹⁰ The actual gases used in some cases had Wobbe numbers that differed from the target values.

5. The SCG report notes that "several of the units tested exhibited more NO_X sensitivities with a greater number of hydrocarbon species in a given HHV/Wobbe Number gas."

The three DTI-sponsored studies (Teekaram et al. 2005; Williams et al. 2004; Williams et al. 2005) report NO_X results for 25 U.K. appliances, several of which contained multiple burners or components (for example, combination boilers and gas fires). Most of the appliances were inuse in residences before testing. The burners were operated on two or three component mixtures (methane plus propane and/or nitrogen) spanning a wide range of Wobbe numbers. Relative to the adjust gas (methane), test gases spanned a Wobbe range of -11 to +10%. The following trends were observed when testing appliances as received:

- 1. All four of the condensing boilers that were noted to have full premix burners had NO_X emissions increase sharply with Wobbe number of the test gas. NO_X increased by factors of approximately 6–10 across the range of gases tested. Increases appeared exponential or bilinear, with the sharpest increases occurring around the Wobbe number of the adjust gas.
- 2. Seven of eight boilers with conventional burners had NO_X emissions that increased (typically linearly) with Wobbe number of the test gas. For these appliances, NO_X increased by a factor of 1.5–2.5 across the range of test gases. An eighth unit—a "back boiler" with radiant ceramic flame—exhibited no major change in NO_X emissions with changing fuel.
- 3. For two of three on-demand water heaters, NO_X increased by a factor of 2 across the range of gases; no appreciable change was seen for the third unit.
- 4. Burners associated with cookers (ranges)—that is, hobs (cooktops), ovens, and grills—had NO_X emissions that were relatively insensitive to the Wobbe number of the test gas; for these burners, NO_X varied inconsistently by factors of 0.5 to 1.5 across the examined range of fuel Wobbe Number.

GTI 2003 indicates that NO_X data were collected but reports results for only one experiment: a long-term test in which three tank water heaters (WH) were operated for four months. A used WH and one of two identical new units (WH2) were operated with a mixture of line gas and propane, simulating an LNG with Wobbe number of 1408. The second identical new unit (WH3) was operated with a typical line gas having a Wobbe number of 1328. NO_X concentrations were consistent for each WH over the four-month course of the test.

The sharp NO_X sensitivity of lean premix burners to changes in Wobbe index is explained by Levinsky (2004), as described above.

6.2.16. Nitrogen Dioxide (NO₂)

The only studies that have presented any results for direct NO_2 emissions are those funded by the U.K. DTI (Teekaram et al. 2005; Williams et al. 2005). Though results for NO_2 are not presented explicitly for all appliances, several trends are apparent. The effect of gas quality (increasing Wobbe number) on direct NO_2 emissions varied by appliance. Overall, NO_2 varied much less than total NO_X . Nitrogen dioxide comprised approximately 10% of total NO_X for most appliances; the major exceptions were the cooker burners and gas fires. In only one of these appliances (an oven) was direct NO_2 reported to increase sharply with Wobbe number

(Williams et al. 2005). Direct NO_2 was reported to decrease with Wobbe number for two live fuel effect fires in which NO_2 was approximately half of total NO_X (Williams et al. 2005).

6.2.17. Soot and Yellow Tipping

Soot formation has been examined at least implicitly in studies dating back to the experiments conducted for the development of AGA and Weaver indices for yellow tipping. However, while yellow tipping indicates soot formation, it may not always translate to significant soot emissions (in the exhaust) or deposition (on component surfaces) as the formed soot can oxidize in the secondary flame area. An example of this is cited in the TIAX (2004a) report on Elba Island. Referring to a 1974 AGA study for the Southern Energy Company, the TIAX report notes "non carbon emitting yellow tipping [was observed] for eight burners" of the 18 tested. The AGA flame code system specifies that a "-4" flame (on a scale of -5 to +5) involves clear yellow tipping with flames that will not deposit soot on impingement. Some decorative gas fires are actually designed to produce a limited amount of soot to provide a decorative orange flame, with subsequent oxidation of the soot in the secondary flame region.

While many U.S. studies have included evaluation of flames for yellow tipping, the research team found only one that included measurement of soot: the TIAX 2003 Cove Point study mentions smoke meter measurements for a vented fireplace.¹¹ By contrast, U.K. studies, including Dutton and Wood (1984) and the recent DTI-sponsored work, have included direct measurement of exhaust soot (using the "soot number") and explicit evaluation of soot deposition on component surfaces.

The Dutton studies of soot used gas fires that were modified to control the amount of primary air and soot formation was determined to be problematic if, after two minutes of operation at a given primary aeration, soot deposition was observed on the "radiant" component¹² (Dutton 1984).

In the recent DTI-funded studies conducted by Advantica, soot was measured using a visual technique in which a pumped sample is compared against standard charts to determine a soot number. Two of the five devices tested in the pilot study (Williams et al. 2004) produced significant amounts of soot. The gas fire produced soot across the range of gases tested, and soot increased at higher Wobbe numbers. The boiler produced soot only at Wobbe numbers of $53-56 \text{ MJ m}^{-3}$ (1420–1490 Btu/scf). For the fire, gases diluted with N_2 had higher soot than gases diluted with CO_2 or methane-propane mixtures with similar Wobbe number. Since these gases had similar Wobbe numbers and in some cases similar levels of propane (representing the NMHC), this result is not explained by the theory that the key determinants of soot production are Wobbe number, through its effect on primary aeration and specific NMHC concentration, which affects the critical equivalence ratio (see Section 5.5).

The Advantica 2005 (Williams et al. 2005) report notes very few measurements of discernible soot in the flue gas, but soot was observed as deposits on surfaces of several appliances. The appliance for which soot was measured most prominently in the flue gas was the live fuel effect

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¹¹ The report does not provide results of the soot measurements; yellow tipping observations are summarized.

¹² Presumably the radiant is the heat exchanger.

(LFE) fire operating on test gases with 17.5% and 22.5% propane. Researchers observed significant soot deposition when the LFE fire was operated on a long-term test that included the equivalent of 10 days continuous operation on a test gas composed of 89.3% methane and 10.7% propane (WN = 54 MJ m⁻³ \approx 1450 Btu/scf). Soot deposits were observed on the coals, at the base beneath the burner assembly, and around the pilot / FSD (flame sensor) assembly.

6.2.18. Methane

The two main DTI studies reported results for methane slip (Williams et al. 2005) or unburned hydrocarbons (Teekaram et al. 2005). The Advantica study (Williams et al. 2005) found low methane levels for most appliances and reported a general trend of increasing methane slip with increasing Wobbe number when methane emissions were observed. BSRIA (Teekaram et al. 2005) reported very low emissions of unburned hydrocarbons without a trend related to gas quality.

6.2.19. Ultrafine Particles and Air Toxics, including Formaldehyde

The research team could find no study examining the effect of gas quality on UFP or formaldehyde formation or emissions. However, Ashman and Haynes (1996) demonstrate that the conditions that lead to increasing formaldehyde emissions are likely to be the same as those that have lead to CO emissions in at least some of existing studies.

6.3. Sensitive Appliance and Burner Technologies

Both fundamental considerations and empirical evidence suggest gas-quality sensitivities to pollutant formation for several basic device designs. From first principles, Levinsky (2004) discussed the CO sensitivity of partial premix (that is, rich premix) burners that are still the most common type in residential appliances. In such burners, an increase in Wobbe number directly leads to primary fuel-air mixtures that are farther from stoichiometric and thus yield higher equilibrium CO at the flame front (Levinsky 2004). The most sensitive appliances are those designed or set to operate with lower primary air ratios—that is, with primary air-fuel mixtures that are more fuel rich. Lean premix burners, which are becoming more common in both residential and small commercial applications for the purpose of NO_X control, are by design very sensitive to the fuel gas Wobbe number (Levinsky 2004). An increase in Wobbe number pushes the lean primary air-to-fuel ratio towards stoichiometric, resulting in higher flame temperatures and sharply higher NO_X emissions. Johnson and Rue (2003) state that devices with closed combustion chambers are very sensitive to CO increases associated with increasing Wobbe number. Here the concern is with the availability of secondary air for complete oxidation of CO and other pollutants formed during initial combustion. Devices in which flame impingement occurs by design or could occur inadvertently with flame lengthening are also of concern, as impingement can inhibit the burnout of CO and other products of incomplete combustion (such as formaldehyde). Some ovens and cooktop burners have this sensitivity.

Empirical evidence about sensitive burners is available from several studies. The BG&E study specifically identified range top pilots and ovens as the most problematic of common in-use household appliances when LNG was introduced in 1978 (Steinmetz 1979). The Alabama Gas Company 1978 study (see TIAX 2004a) noted flame lengthening and yellow tipping of the pilot for the one cooktop burner tested; lengthening of the water heater pilot interfered with the secondary air supply for the main burner, producing yellow tipping with LNG (TIAX 2004a).

Among the appliances tested in the DTI-sponsored studies in the U.K., almost all of the boilers showed substantial sensitivity to CO increasing with Wobbe number. In the recent U.K. and SCG studies, appliances with lean premix burners showed sharp sensitivity to NO_X emissions increasing with higher Wobbe number fuel gas.

6.4. Factors Associated with In-Use Equipment

There are several characteristics of in-use equipment that can be important in considering gas interchangeability. The first is that most (if not all) new appliances are de-rated—that is, set to deliver fuel energy at a rate that is below the nominal input rate at sea level. The purpose of this de-rating is to ensure a margin of safety that allows for: (1) variable field conditions, including locations having line gases with higher Wobbe numbers, and (2) the effect of environmental variables, notably ambient temperature, humidity, pressure, and elevation (for which further de-rating is recommended and often, but not always implemented). This de-rating is widely recognized in the industry and supported by service technicians who maintain these settings. De-rated appliances have some capacity to use higher Wobbe gases; however the use of higher Wobbe gases will reduce the margin of variability that can be accommodated for environmental factors.

Appliances operated at elevation potentially present a special problem. To accommodate lower concentration of atmospheric oxygen associated with a decrease in atmospheric pressure at elevation, appliances are supposed to be de-rated at 4% per 1000 feet (at elevations above 2000 feet). The field efforts of the Public Service Company of Colorado showed that many appliances were not adequately de-rated for elevation. Such inadequate de-rating creates a baseline situation in which many appliances may be operating with a rich fuel-air mixture; an increase in Wobbe number of the supply to such locations would be expected to lead to incomplete combustion in at least some appliances. The relevance of this concern to California is unclear but deserving of some consideration.

A critically important group of considerations for in-use appliances is factors related to aging and service. Residential appliances are not serviced regularly, may be installed and adjusted incorrectly, and can degrade over time as components get dirty (for example, via soot deposition), worn and possibly deformed from repeated heating or overheating, or become misaligned (for example, during cleaning or movement). Burner problems short of outright failure may not be detected for extended periods and may not be repaired even after they are detected, owing to cost and time constraints. The two recent reviews of IX issues (NGC+ 2005; Williams 2006) both identified in-use aging and maintenance issues as a major concern.

Several laboratory-based studies have examined used appliances obtained from residences. The recent U.K. DTI studies focused almost entirely on used appliances. Several were received in a condition that required service, and several had very high CO emissions on the baseline adjust gas; these groups overlapped but were not identical. Interestingly, some of the appliances had problems that were not detected during servicing, and, for at least one appliance, servicing led to higher emissions. The recent TIAX studies for Elba Island (TIAX 2004a) and Cove Point (TIAX 2003) both included testing of appliances intentionally misadjusted to simulate potentially problematic operation modes (e.g., blocked heat exchangers and closed air shutters).

Field studies support the concern that appliances with impaired combustion conditions may be especially sensitive to changes in gas quality. The report of Steinmetz (1979) about BG&E

experience associated with LNG introduction in 1978 offers direct evidence of adverse impacts associated with in-use appliances. The Atlanta Gas Light 1975 study observed incorrect orifices, closed air shutters, and clogged heat exchangers (TIAX 2004a). The NGC+ (2005) report cites two additional field studies—a Massachusetts studied referred to as "Commonwealth" and a study conducted by SCG in the 1990s—that support this concern; although the research team was not able to obtain or review documentation of these studies, the authors reporting these results are credible and suggest firsthand knowledge of the original work or documentation.

6.5. Important Operating Modes

There is some evidence in the existing literature that exhaust concentrations of CO can be much higher when a burner is first fired (warm-up) than during hot stabilized operation. An example of this is seen in Figure 6 of the Washington Gas Light study (Rana and Johnston 2003). This figure shows that for the storage water heater tested, CO was substantially higher during the first 6-14 minutes, relative to concentrations measured during fully warmed operation; warmup time varied substantially among the gases tested. Another example of transient effects is shown for an oven on p. 60 of the TIAX (2004) Elba Island report; this plot shows that almost all of the CO emissions are associated with the first few minutes of appliance operation. The importance of such transient effects will depend on specific burner operating cycles. Transient emissions are less important for devices that quickly reach hot stabilized burner operation and that have burners that are commonly fired for longer periods. By contrast, devices that require long warm-up times or operate on many short burner cycles (such as tankless water heaters) may have transient emissions that comprise a more substantial fraction of total emissions from the device. It is important to note that the effect of changing gas quality on transient emissions can go in either direction. A higher Wobbe gas may cause an increase in combustion temperatures that leads to a more rapid heating of the burner head and other surfaces on which the flame is impinging; this more rapid heating may in turn reduce the time over which elevated CO is seen. The aforementioned oven tested by TIAX (2004) appears to show this effect for operation with Algerian LNG versus SNG line gas.

6.6. Dilution of LNG with N₂, CO₂ or Air

Several of the gas interchangeability studies conducted in recent years have examined the effect of adding either N₂, CO₂, or air as an inert diluent to reduce the heat value and Wobbe number of actual or simulated LNG blends. The first general finding is that such dilution (sometimes referred to as *ballasting*) is an effective method to achieve interchangeability of imported LNG in existing residential appliances. This finding is supported by direct experimental evidence in the GTI 2003 study (Johnson and Rue 2003), the Cove Point study (TIAX 2003), the Elba Island study (TIAX 2004a), and all three of the U.K. DTI-funded studies (Teekaram et al. 2005; Williams et al. 2004; Williams et al. 2005). The second general finding is that the three are, for the most part, similarly effective in addressing emissions of CO and NO_X. The GTI 2003 study directly compared mixtures diluted with air or nitrogen and the Advantica Pilot Study (Williams et al. 2004) specifically compared CO₂ and N₂. There are, however, two caveats to this last point. The first is that the gas fire tested by Williams et al. (2004) had much higher soot emissions when operating on mid- to high-Wobbe gases containing 6% N₂, compared with operation on similar Wobbe gases containing 6% CO₂. The second caveat is that the Condensing Boiler 1 tested by Williams (2005) had much higher CO using high Wobbe (52–54 MJ m⁻³, ~1400–

1450 Btu/scf) gases with N_2 compared with methane-propane gases in the same Wobbe number range.

Ballasting of natural gas supplies to reduce the heat input rate has been occurring in practice for a number of years. Xcel Energy (Colorado) adds air to pipeline gas to reduce the heating value to levels encountered historically in the service area (Halchuk 1996). Southern LNG and Washington Gas Light are adding N_2 at levels of a few molar percent to imported LNG to achieve the gas quality limits determined as sufficient in the studies described above.

6.7. Prediction of IX Effects Using Existing Indices

The Weaver and AGA indices retain value as they relate to and depend on basic combustion phenomena. Their value may be limited for appliance technologies that differ from the partial premix burners for which they were initially developed. It is possible, though not necessarily the case, that testing of new appliance technologies may show the index formulations to be relevant to a wider range of devices.

The recent GTI study (Johnson and Rue 2003) intended to examine the degree to which AGA and Weaver indices predict modern appliance responses to gas quality changes. However, since only one of the tested appliances had high emission with any combination of adjust and test gases, this question could not be fully evaluated. Nevertheless, they reported that the most relevant index for CO was the AGA yellow tipping index; Weaver J_H, J_L, and J_Y also "correlated well with the data" from their appliance tests.

TIAX (2004a) notes in their study for Elba Island that the measured CO emissions correlate better to the Weaver incomplete combustion index than to the Wobbe number of the test gas. TIAX used the Weaver index approach, combined with new experimentation, to recommend gas quality guidelines for Cove Point and Elba Island distribution areas. For LNG, the key limits are on the heat input rate (J_H , equal to Wobbe ratio), the incomplete combustion index (J_I), and the yellow tipping index (J_Y); the lifting index (J_L) can be important in some cases.

The ICF and SI of Dutton were developed for U.K. appliances. However, since the basic technology is similar to U.S. domestic/residential appliances, it may be worthwhile to investigate the applicability of the ICF and SI to U.S. devices. Levinsky's metrics of CO index and GSI should also have relevance to U.S. residential appliances. The fact that the GSI and ICF yield similar conclusions about acceptability of specific gas mixtures reinforces the value of each metric.

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8.0 Glossary

ANSI American National Standards Institute

BBU Back boiler unit

BG&E Baltimore Gas & Electric

British thermal unit Btu

CE-CERT Center for Environmental Research and Technology

CPUC California Public Utilities Commission

daf dry, air-free

FSD a flame sensor

FVIR flammable vapor ignition resistant

GCV gross calorific value

GSI Gasunie Soot Index

GTI Gas Technology Institute

Η heating value HC

HHV higher heating value

ICF incomplete combustion factor

IGT Institute of Gas Technology

LBNL Lawrence Berkeley National Laboratory

hydrocarbons

live fuel effect fire LFE

LI lifting index

LNG liquefied natural gas

 $MJ m^{-3}$ megajoules per cubic meter

NG natural gas

nm nanometer

NMHC non-methane hydrocarbons

ODS oxygen depletion sensor

Pacific Gas & Electric PG&E

PSC Public Service Company

RH relative humidity

scf standard cubic foot

SCG Southern California Gas

SI sooting index

SLNG Southern Liquefied Natural Gas

TTB temperature sensor

UCR University of California at Riverside

UFP ultrafine particle

W Wobbe number

WGL Washington Gas Light

WH water heaters

Appendix A

Residential Natural Gas Appliance Technologies

APPENDIX A

Residential Natural Gas Appliance Technologies Prepared by Alex B. Lekov and Gabrielle Wong-Parodi

Residential natural gas (NG) appliances have been identified as sensitive to fuel supply changes owing to their long lifetimes, infrequent maintenance, and lack of feedback control. This section reviews the component technologies that are most common in residential appliances.

1.1 Product Classes

Table 1 summarizes the most common residential NG appliances in California, organized by category. Also included are commercial cooking products. This section describes the burners and other technologies used in these products.

Table 1. Residential natural gas appliances and products.

Category	Products
Cooking Products	Cooktop, Oven, Range
(Residential)	
Cooking Products	Cooktop, Oven, Range, Fryers, Griddles, Broilers,
(Commercial)	Braising Pans
Water Heaters	Storage, Tankless (on-demand)
Central Furnaces	Furnace, Mobile Home Furnace
Clothes Dryers	Clothes Dryer
Pool Heaters	Pool Heaters
Direct Heating Equipment	Floor or Wall Furnace, Space Heater, Hearth Products
Other	Boiler, Radiant Patio Heater, Outdoor Grill

Cooking products (residential and commercial), water heaters, furnaces, and clothes dryers represent the vast majority of gas appliances found in California residences. This review focuses primarily on these four product categories. The other products listed play a smaller role in the California gas appliance market, but some are considered for possible localized effects, such as carbon monoxide (CO) emissions into a home where the device is used, or possible collective effects, such as nitrogen oxide (NO_X) emissions from pool heaters in areas of Southern California where ozone is a persistent problem (NO_X is a key ingredient of atmospheric ozone formation). They also may use different types of burner systems and other technologies that may react differently to gas supply changes.

Design Components

Appliances are comprised of design components (burners, heat exchangers, and venting systems) that affect the combustion process and that may be impacted by variations in the properties and composition of supply gas. This section describes the various design components and Section 1.4 describes their potential importance for gas interchangeability.

Burner Components

A gas appliance burner system must accomplish the following: (a) control and regulate the flow of gas, (b) assure the proper mixture of gas with air, and (c) ignite the gas under safe conditions. Appliance burner systems can be divided into six main components, illustrated in Figure 1 below. The technologies associated with each component are described subsequently.

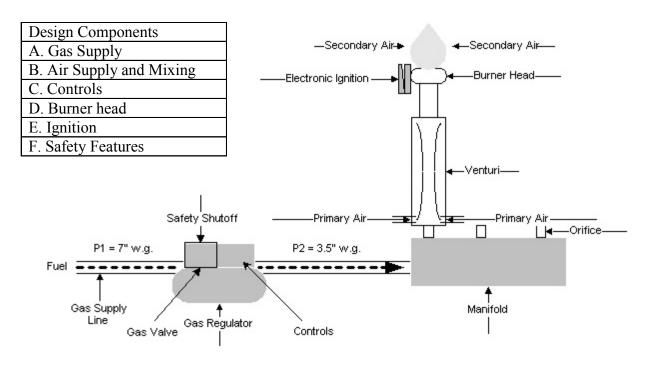


Figure 1. Typical gas appliance burner system.

A. Gas Supply

As shown in Figure 1, there are three main parts to the gas supply system: (1) gas/burner supply line, (2) gas regulator, and (3) gas valve.

Gas/burner supply line. The gas supply line runs from the meter outside of the home through to the gas valve within the residential gas appliance; it often includes an external shut-off valve to which the appliance is connected. The pressure in the gas supply line is 7 in H_2O (inches of water), which is the U.S. standard pressure that is delivered from the gas meter to households. The regulator controls the pressure of the gas being delivered to the burner supply line, which is

typically less than the pressure supplied to the appliance. The burner supply line runs from the gas valve to the manifold, which distributes gas to the burners. The orifices regulate the flow of gas to individual burners based on the size of the orifice opening and the pressure upstream of the orifice (typically 3 to 4 in H₂O).

The gas regulator is a spring-loaded, dead-weighted, or pressure-balanced device that can maintain the gas pressure to the burner supply line within $\pm 10\%$ of the design operating pressure at any one rate from maximum to minimum firing (gas input) rates. The pressure from the burner line through the manifold remains constant. There are three types of regulating devices: adjustable, multi-stage, and non-adjustable. As the names suggest, adjustable regulators allow external adjustment across a range of outlet pressure settings, multistage regulators can be positioned to two or more outlet pressure settings, while nonadjustable regulators are preset to a single outlet pressure.

The gas valve controls gas flow. The gas valve can be on/off or modulating (that is, controlling of the gas flow rate).

Manual and automatic safety shut-off valves also may be contained part of the gas supply system. Safety shut-off valves are described in more detail in the Safety Features section.

B. Air Supply and Fuel-Air Mixing

Burners can be classified according to the extent to which combustion air is mixed with gas before the mixture emerges from the ports (individual holes) of the burner head. The mixture types most applicable to residential gas appliances are (1) *partial (rich) premix*, (2) *lean (full) premix*, and (3) *non-premix (non-aeration)* burners. Figure 2 shows an example of the three burner fuel/air mixture types.

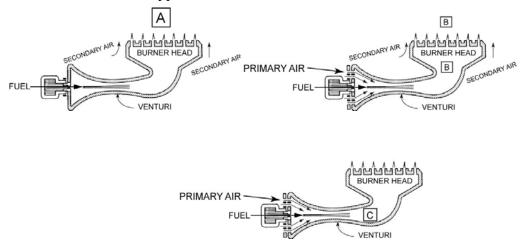


Figure 2. Fuel/air mixture types: (A) Non-aeration, (B) Partial premix, and (C) Lean premix.²

In *partial premix* burners, a fraction of the air required for complete combustion is provided upstream of the burner head; the remainder is drawn in from around the flame. Air added before combustion is called "primary"; air drawn in from around the flame is termed "secondary." In

conventional appliance burners, the pressurized gas flows through the orifice of a nozzle into a venturi where the primary air is pulled in. Fuel and primary air mix while accelerating through the venturi. This mixture exits the burner port, and combustion begins as it confronts the flame front in the primary combustion zone. The combustion process is completed as secondary air diffuses into the flame front. In the partial premix burners used in residential appliances, primary air typically provides 20%–60% of the total air required for complete combustion. The amount of air that can be provided as primary air is limited by the size of the gas supply orifice and the availability of secondary air.

In *lean premix* burners the fuel and all of the air required for combustion are mixed upstream of the combustion zone. The amount of premix excess air sets the fuel-air ratio at which primary combustion occurs, allowing for control of flame temperature and NO_X and CO production.

In *non-aeration* burners the gas mixes with the air only after it has passed through the burner head. This technology is used in some pilot-burners to avoid the tendency of the small air openings required for a pilot flame to become blocked with dirt, lint, cooking residues, and so forth. These types of burners have a characteristic hard blue flame.

C. Controls

Residential gas appliance burners have three types of burner controls: (1) *on/off*, (2) *modulating*, and (3) *flame height adjustment*.

On/Off control is used in devices that are turned on/off manually, such as clothes dryers, or automatically, such as water heaters; the switch can be located either directly on the appliance or in an easier to access location. Modulating controls allow variable fuel input rates. This type of control is commonly found in space heating appliances where it allows use of the same amount of energy while reducing the number of cycles to optimize input over time; this can improve the comfort level for occupants. Flame height adjustment (a type of modulating control) is specific to cooking products and hearth products that feature a decorative flame.

D Burner Head

The burner head contains the ports though which the primary gas-air mixture (for a premix flame) or just the gas (for a non-aeration flame) is conveyed to the combustion zone. Residential appliance burner heads can be grouped as follows: (1) *single-port (in-shot)*; (2) *multi-port (circular, tube, or other geometry)*, (3) *radiant*, and (4) *power*.

In *single-port (in-shot)* burners, fuel and air are mixed inside of the burner tube, ignited at the outlet of the burner then directed into a heat exchanger.

Multi-port burners include the circular heads common to storage water heaters and cooktops, long tubes commonly used for ovens and grills, and blade-type burners used in boilers.

Figure 3 shows examples of the single-port and multi-port types of burner heads.³



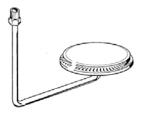


Figure 3. Examples of single-port (in-shot) and multi-port/circular burners.^{2,4}

Radiant gas burners (sometimes called infrared burners) are common in heating applications and sometimes also used in cooking appliances. In a radiant burner, combustion occurs at the surface of a perforated ceramic tile or stainless steel mesh; these surfaces are designed to evenly disperse the fuel/air mixture. All required combustion air is provided through the burner; they are thus fully premixed. Heat transfer can occur through both radiant and convective energy processes. For example, a radiant cooktop burner provides radiant energy through a glass-ceramic plate overlying the ceramic tile on which combustion occurs. Convective heat transfer occurs as the combustion products are jetted through the perforated glass-ceramic plate.

Power burners are common in commercial cooking appliances. The power burner contains all burner components and a fan in one unit. A power burner operates much in the same way as a radiant gas burner, but power burners use a blower to force the required fuel/air mixture ratio into the burner.

E. Ignition

Four types of ignitions systems are used in residential gas appliances: (1) *permanent pilot*, (2) *electronic*, (3) *electric glo*, and (4) *light by hand*.

A *permanent pilot* is a small auxiliary gas burner that provides a constant flame to ignite a larger gas burner. There are two types of pilot burners: primary-aerated and non-aerated, whose operation is consistent with main burner aeration systems described above. Primary-aerated pilots typically have a screened air opening that can get plugged with lint, dust, and other debris and must be cleaned periodically.²

Electronic ignition systems are frequently used with residential gas appliances; common variations include intermittent pilot ignition, intermittent direct ignition, and hot surface ignition. Intermittent pilot ignition uses a spark to light a temporary pilot flame, which in turn lights the main burner. Intermittent direct ignition lights the main burner directly by generating a spark. Hot surface ignition lights the main burner directly from a hot surface and functions as a flame detection device.

Electric glo ignition uses a carbide "glo" type igniter that works when 120 volts is applied to the igniter. Once the igniter draws 2.9 amps, the hot "glo" igniter ignites the burner.

Light by hand requires the user to provide a supplemental flame or spark while opening the gas supply valve; this type is found only in older appliances.

F. Safety Features

We have identified five main types of burner safety devices: (1) flammable vapor ignition resistance (FVIR) (specific to water heaters), (2) safety shutoff, (3) thermal cut-off or energy cut-off, (4) safety pilot, and (5) oxygen depletion sensor.

Flammable vapor ignition resistance (FVIR) water heaters use a sensor placed inside the combustion area to detect ignition of a flammable vapor from outside the appliance and shut off the flow of gas to the burner and pilot light. After July 1, 2003, all U.S. storage water heater manufacturers were mandated to include the FVIR in all water heaters. FVIR water heaters still comprise a minority of in-use devices, but saturation will increase steadily as old units are replaced.⁵

A *safety shutoff* device stops the gas supply to the burner(s) if the ignition source fails. This device can interrupt the flow of gas to main burner(s), pilot(s), or both.

A thermal cutoff switch (referred to as the "over-limit switch") is designed to shut the unit down when it senses excessive temperatures inside the combustion chamber. The device functions as a thermal fuse (one time operation). Cutoff points are achieved by formulating a pellet that melts at very specific temperatures. Some water heaters are equipped with an energy cut-off switch to prevent over-heating of the tank water. If the water temperature exceeds 200°F, the temperature sensitive fuse will melt, interrupting power to the power unit coil and stopping gas flow to the pilot and main burner. Safety pilots provides an ignition flame for the main burner and heat the thermal cut-off switch to ensure safe operation.²

Oxygen depletion sensors (ODS) are designed to prevent accidental carbon monoxide poisonings by shutting down the appliance when the oxygen concentration in air drops below a specified level; such oxygen depletion is used as a marker of improper ventilation and a build-up of combustion exhaust. ODS systems have three main components: (1) an oxygen sensitive pilot burner, (2) a thermocouple positioned in the pilot flame; and (3) a safety shutoff valve.⁶

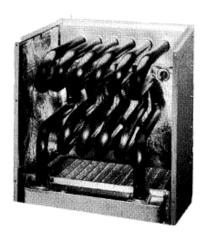
Heat Exchangers

A heat exchanger transfers energy from hot combustion gases to water or air for various applications. In many residential appliances combustion occurs directly within the heat exchanger. There are six main types of heat exchangers: (1) *individual section*, (2) *tubular*, (3) *serpentine or clamshell*, (4) *cylindrical*, (5) *central flue*, and (6) *finned copper/aluminum tube*.

In furnaces and tankless water heaters, the heat exchanger is usually made of cold-rolled, low-carbon steel. In storage water heaters, the heat exchanger is made of a single flue that is located in the center of the water heater tank. In pool heaters, the heat exchanger is made of copper.

An *individual section heat exchanger* is comprised of a number of separate heat exchangers with separate burners. The sections are joined below to allow a common ignition system to light all burners and joined above where exhaust gases are directed to a common flue. The *tubular and serpentine heat exchangers* (appliances such as furnaces, boilers, and pool heaters) are variations of the individual section type that are used exclusively on gas-burning equipment. Figure 4 shows pictures of typical individual section, tubular, and serpentine (clamshell) heater exchangers.²





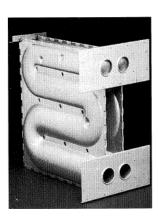


Figure 4. Examples of individual section, tubular, and serpentine (clamshell) heat exchangers.²

A *cylindrical heat exchanger* has a single combustion chamber and uses a single-port burner. Cylindrical heat exchangers are used on gas and oil units. In the last 15 years, it is uncommon to find residential gas appliances with a cylindrical heat exchanger.

A *central flue heat exchanger*, found in storage water heaters only, is a long cylindrical passage where exhaust gases pass from the combustion chamber to the draft hood inlet opening on an appliance equipped with a draft hood or to the outlet of the appliance. Figure 5 shows a typical central flue heat exchanger.¹

A *finned copper/aluminum heat exchanger*, found in pool heaters is a thin fin wrapped around a pipe where the cool water enters. After passing through the heat exchanger, the now-warmed water is delivered to the pool.⁷

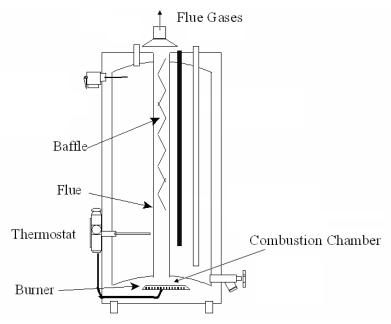


Figure 5. Water heater with central flue heat exchanger.

Venting Systems

A vent system is a continuous open passageway from the flue collar or draft hood of a gasburning appliance to the outside atmosphere for the purpose of removing flue or vent gases. There are four main types of venting systems: (1) *natural draft*, (2) *mechanical (induced, forced, or power)*, (3) *direct vent*, and (4) *ventless*.

In *natural draft* systems, the draft is created as hot exhaust gases rise through ducting that is open to the atmosphere. *Mechanical draft* systems create draft by a fan; there are three main types: *induced, forced, and power*. An *induced draft system* uses a fan (located within the appliance) to cause the removal of flue or vent gases under non-positive static vent pressure, whereas *forced draft systems* operate under positive static pressure; both of these draft systems are, in general, vented vertically. *Power draft systems* uses a fan (located within the vent) to cause the removal of flue or vent gases under positive static pressure and are, in general, vented horizontally. *Direct venting systems* are appliances that are constructed and installed so that all air for combustion is derived directly from the outside atmosphere and all flue gases are discharged to the outside atmosphere. *Ventless* burners include cooktops, some gas ovens, and certain gas fireplaces.

1.3 Summary of Appliance Technologies

Tables 2 and 3 summarize important features of residential and commercial cooking appliance technologies, respectively.

Table 2. Residential gas appliance technologies

Residential		Burners						Typical
Gas Products	Fuel/Air Controls Mixture		Burner Ignition Head		Safety Features	Exchanger		Input (Btu/h) ⁸
Cooktops	Partial premix (standard) or Lean premix (radiant)	On/Off or Modulating (manual)	Multi-port (Circular) or Radiant	Electronic Ignition or Pilot	Safety Shut- off	None	None (draft hood)	9,000
Ovens	Partial premix (standard) or Lean premix (radiant)	On/Off or Modulating (manual or automatic)	Multi-port (or Radiant (uncommon)	Electronic Ignition or Pilot	Safety Shut- off or Thermal Cut-Off	None	None (draft)	11,000
Clothes Dryers	Partial premix - (typical)	On/Off *	Single-port	Electronic Ignition or Pilot	Safety Shut- off or Thermal Cut-Off	None**	Mechanical - induced	24,000
Storage Water Heaters	Partial premix - (typical)***	On/Off	Single-port or Multi-port (circular)	Electronic Ignition or Pilot	Safety Shut- off, Energy Cut-Off or TVIR	Central Flue	Natural, Direct, or Mechanical - power	20,000 – 75,000
Tankless Water Heaters	Partial premix - (typical)	On/Off and/or Modulating (automatic)	Single-port or Multi-port (Ribbon)	Electronic Ignition	Safety Shut- off or Thermal Cut-Off	Tubular	None or Mechanical - power	100,000 – 200,000
Central Furnaces	Partial Premix - (typical)	On/Off or Modulating	Single-port or Multi-port (Ribbon)	Electronic Ignition or Pilot	Safety Shut- off or Thermal Cut-Off	Clamshell, Serpentine, or Tubular	Natural, Direct, or Mechanical	30,000 – 225,000
Hearth	Partial premix, Lean premix (radiant) or Non-aeration	On/Off or Flame Height Adjustment	Single-port, Multi-port, or radiant	Electronic Ignition, Pilot or Light by Hand	Safety Shut- Off	None	None or Natural	10,000– 60,000
Pool Heaters	Partial premix and Lean premix (radiant)	On/Off	Multi-port or radiant (rare)	Electronic Ignition	Safety Shut- Off	Individual (finned copper tube	Natural (direct exhaust)	250,000

^{*}The on/off control can be controlled by a moisture sensor.

**Hot flue gases are mixed with a large amount of air and are forced through the dryer tumbler.

***This year (2006) South Coast Air Quality Management District (SCAQMD) will mandate low-NOx water heater limits, which will require all new water heaters to use lean premix.

Table 3. Commercial gas cooking appliance technologies

Commercial	gas cooking	Heat	Venting	Typical				
Gas	Fuel/Air	Controls	Burner	Ignition	Safety	Exchanger		Input (Btu/h)
Products	Mixture		Head	_	Features			
Fryers	Partial premix (standard) or Lean premix (radiant)	On/Off	Multi-port, Radiant or Power Burners	Electronic Ignition	Thermal Shut-Off	Central flue	None (draft hood)	20,000 (open deep fat fryer) 18,000 (pressure/kettle) 14,000–54,000 (flat bottom)
Griddles	Partial premix (standard) or Lean premix (radiant)	On/Off or Flame Height Adjustment	Multi-port or Radiant	Electronic Ignition	Thermal Shut-Off	None	None (wall canopy)	34,000
Broilers	Lean premix (radiant)	On/Off or Flame Height Adjustment	Radiant	Electronic Ignition	None	None	None (wall canopy)	70,000 (overfired) 80,000 (underfired)
Cooktops	Partial premix (standard) or Lean premix (radiant)	Flame Height Adjustment	Multi-port (Open or Closed), Power or Radiant	Electronic Ignition or Pilot	Safety Shut- off	None	None (draft hood)	20,000–25,000 (open) 20,000–40,000 (closed) 45,000 (radiant)
Chinese (Wok) Ranges	Partial premix (standard)	Flame Height Adjustment	Multiport or Power	Electronic Ignition or Pilot	Safety Shut- off	None	None (draft hood)	53,000 (<18 in) 110,000 (>20 in) 150,000 + (power)
Ovens	Partial premix (standard) or Lean premix (radiant)	On/Off	Multi-port or Radiant	Electronic Ignition or Pilot	Safety Shut- off	None	None (draft hoods and except pizza/deck)	7,000–25,000 (standard) 21,000 (deck) 68,000 (conveyor) 30,000 (rotisserie)
Braising Pans	Partial premix	On/Off	Multiport	Electronic Ignition	Safety Shut- off	None	None (wall canopy)	40,000

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